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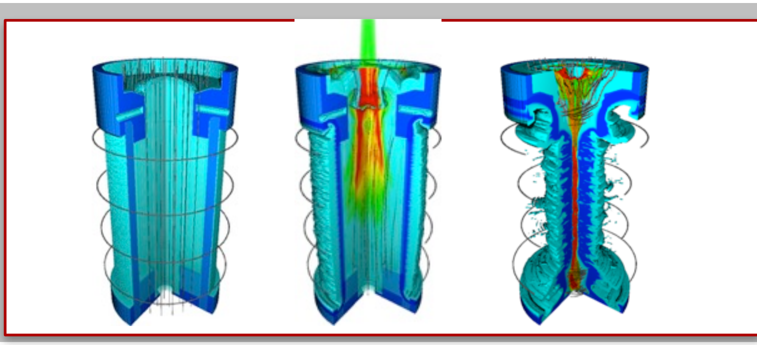

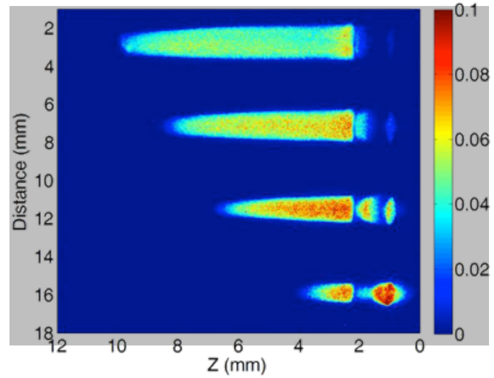

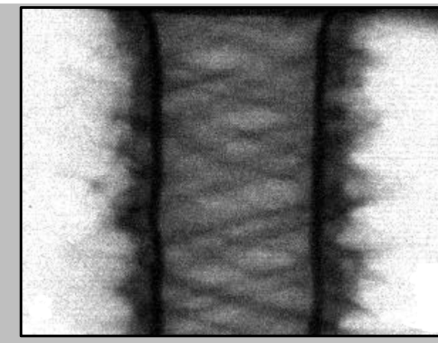

Progress and Plans for Improving Laser Preheating in MagLIF

K.J. Peterson, D.H. Barnak, E.M. Campbell, P.-Y. Chang, J.R. Davies, M. Geissel, C.S. Goyon, S. B. Hansen, A.J. Harvey-Thompson, C.A. Jennings, B.G. Logan, J. Moody, T.N. Nagayama, B.B. Pollock, J.L. Porter, A.B. Sefkow, I.C. Smith, D. Strozzi, and M.-S. Wei

Sandia National Laboratories, Albuquerque, NM, USA

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Lawrence Livermore National Laboratory, Livermore, CA, USA

Anomalous Absorption Conference

Old Saybrook, CT, May 1-6, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Summary

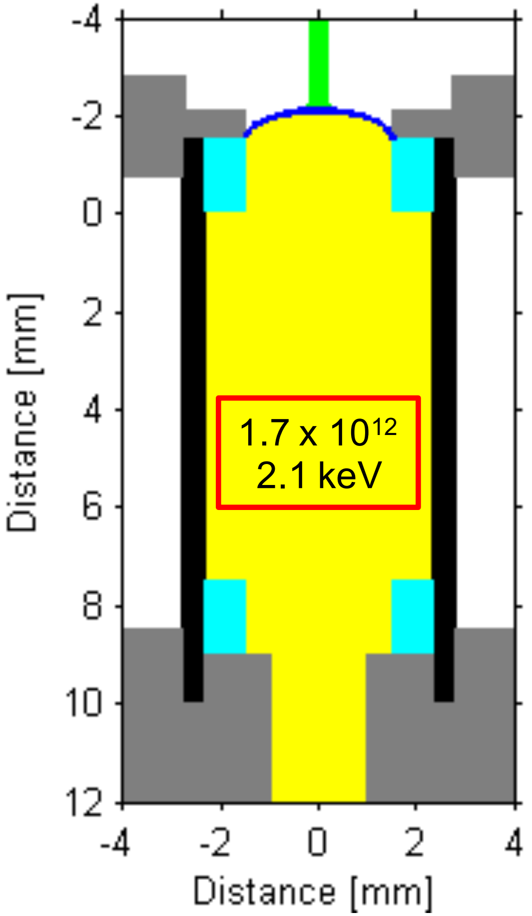
- We have made significant progress in our understanding of integrated MagLIF implosions since our first successful experiments
  - Laser induced mix can significantly degrade integrated performance and becomes more and more problematic as laser energy coupling increases
  - In targets with all low-Z components, performance appears to scale with drive current and laser energy coupling
  - Simulations must assume only a fraction of the laser energy is coupled to the fuel to obtain qualitative agreement (unconditioned beam)
  - Initial attempt of using a DPP to smooth the beam did not improve performance, but is consistent with recent simulations

Summary (continued)

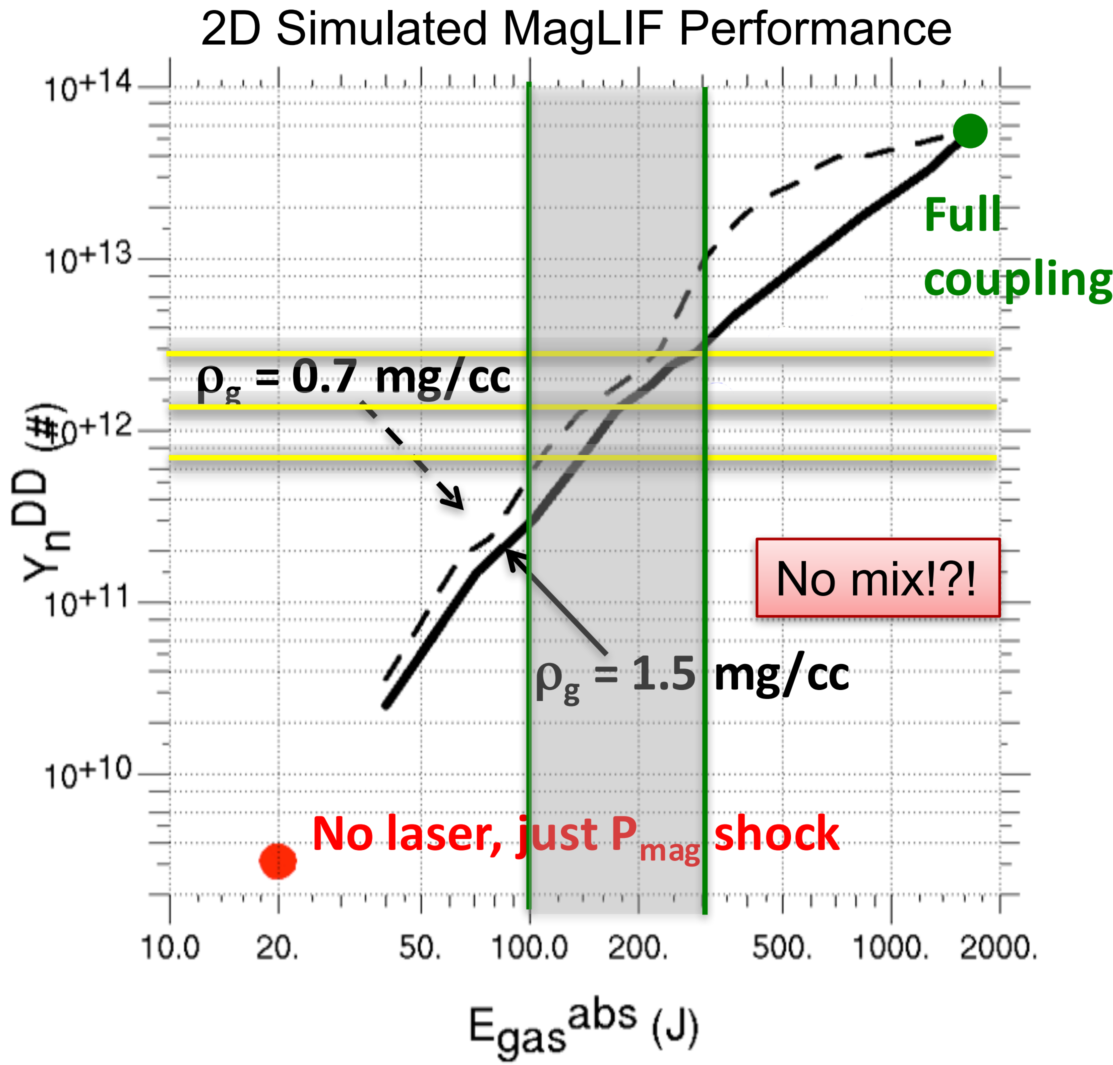
- Laser heating experiments being performed on multiple facilities have already produced significant insight, however, significant uncertainties and questions remain
  - (Z, PECOS) experiments with phase plates show improved energy coupling and are closer to simulation predictions, but still are generally in poor agreement.
  - OMEGA-EP and NIF preheating experiments appear to agree reasonably well with simulation predictions.
  - These experiments will be the focus of the subsequent talks today

- A plan is currently underway to develop a new baseline MagLIF platform and laser pulse shape with a DPP conditioned beam

The baseline MagLIF experiments produced interesting stagnation conditions

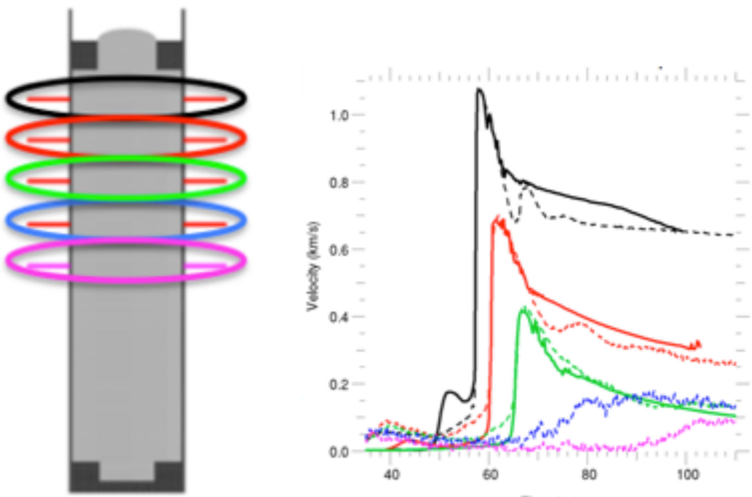


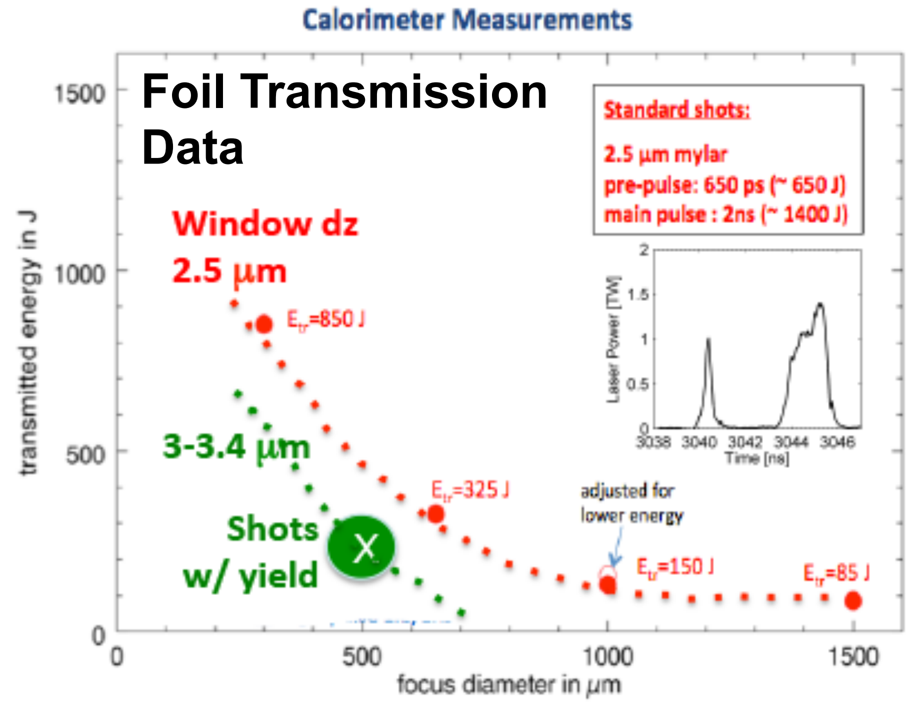
Baseline Target Parameters
Window thickness = 3.5 μm
Target height = 7.5 mm
Laser energy = 2.5 kJ
Endcap material = aluminum

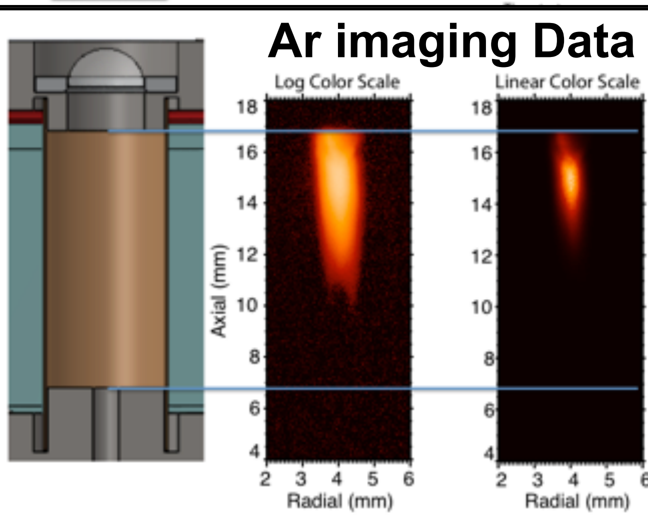


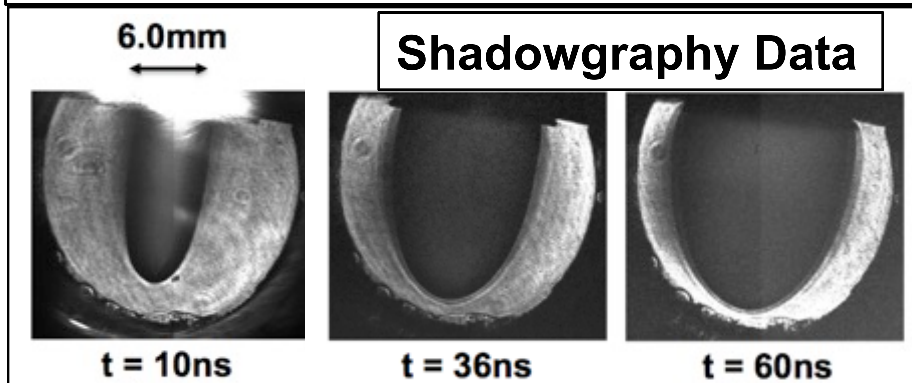
A. B. Sefkow et al., Phys. Plasmas, 21 072711 (2014).

Laser-only experiments appear to confirm poor laser-fuel coupling in initial experiments: Multiple measurements are consistent with low energy coupling (~10-20%)

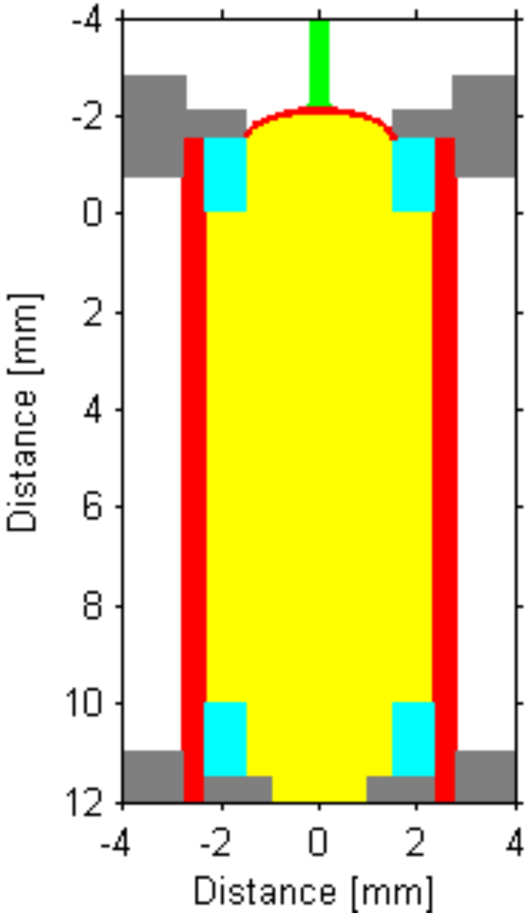








Reducing the window thickness by 2x did not improve performance



1.7×10^{12}
2.1 keV

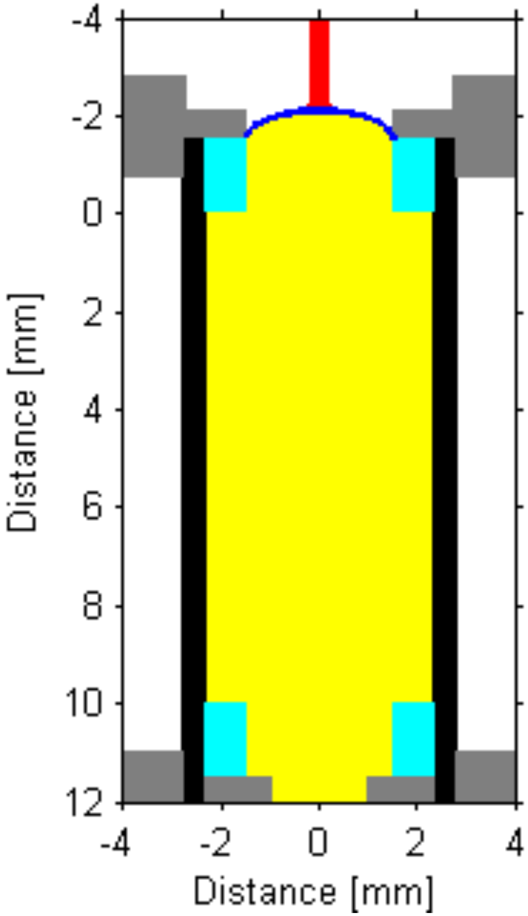
Height
7.5 to 10 mm

Window
3.5 to 1.7 µm

2.5×10^{11}
1.5 keV

Baseline Target Parameters
Window thickness = 3.5 µm
Target height = 7.5 mm
Laser energy = 2.5 kJ
Endcap material = aluminum

Increasing laser energy to the target further decreased performance



1.7 x 10^{12}
2.1 keV

Height
7.5 to 10 mm

Window
3.5 to 1.7 μm

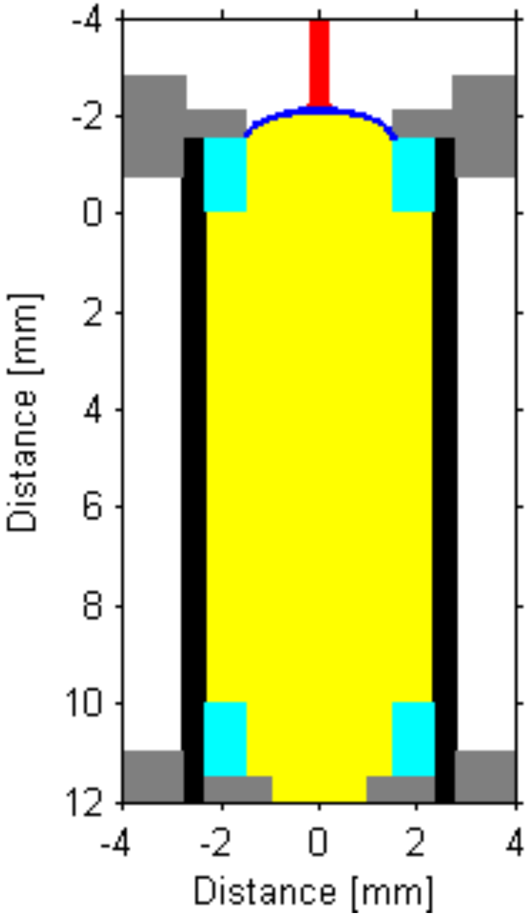
2.5 x 10^{11}
1.5 keV

Laser
2.5 to 4 kJ

1.1 x 10^{11}
1.1 keV

Baseline Target Parameters
Window thickness = 3.5 μm
Target height = 7.5 mm
Laser energy = 2.5 kJ
Endcap material = aluminum

Increasing laser energy to the target further decreased performance



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Laser
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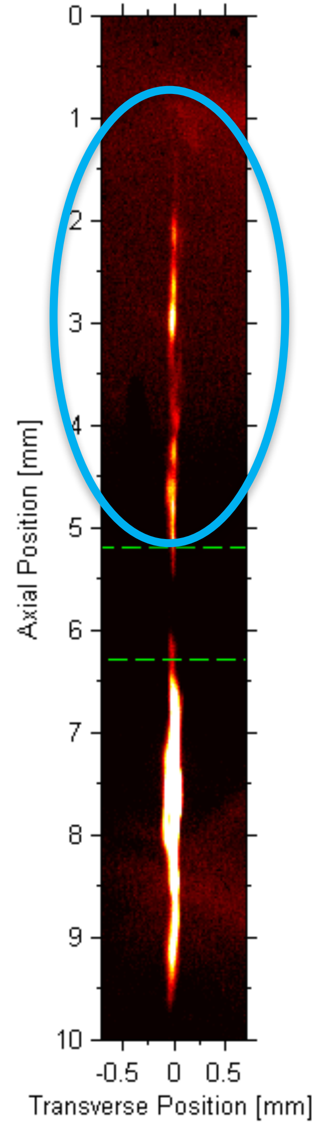
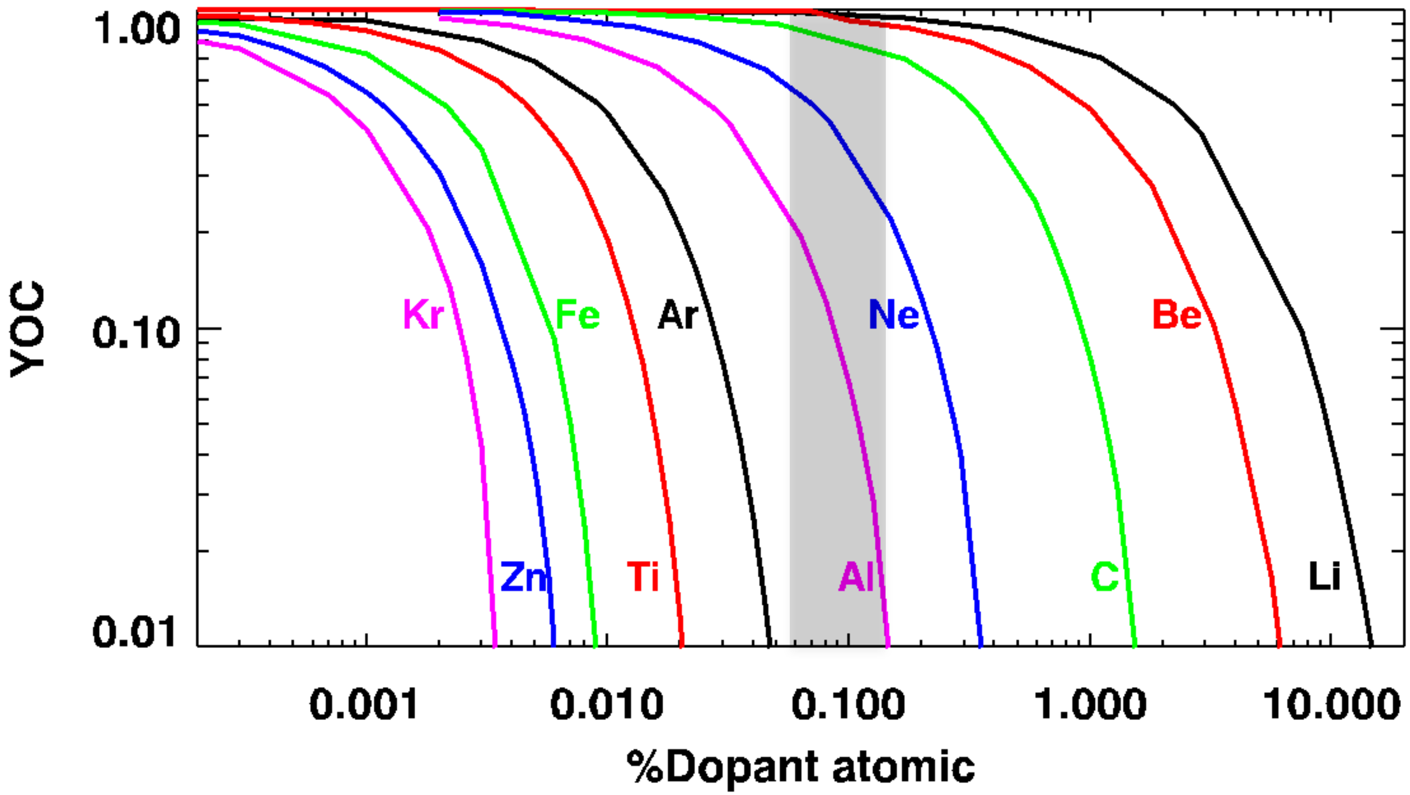


Stagnation image has weak emission near top endcap

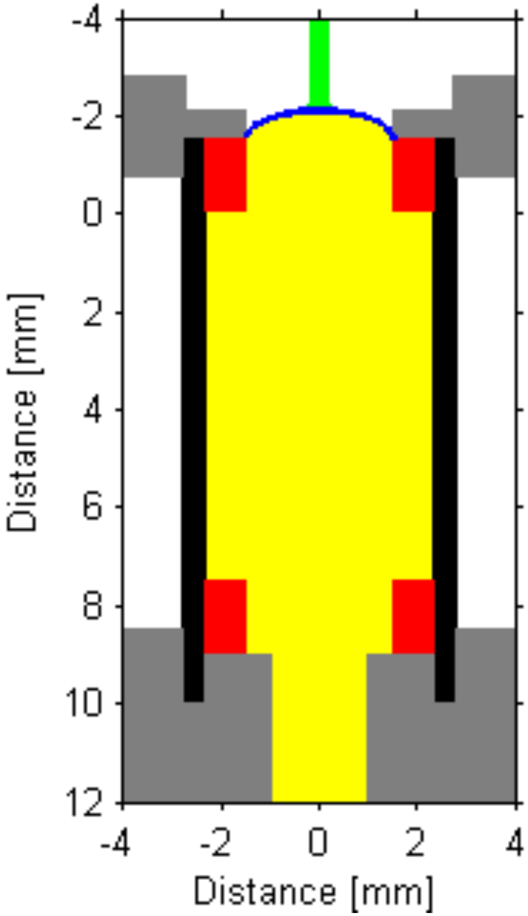
This is consistent with laser induced mix

With its long preheat stage, MagLIF is highly susceptible to fuel impurities (mix)



Even small high-Z fractions lead to catastrophic radiative losses during the ~50 ns preheat stage. *We must determine and quantify all sources of mix, starting with mix induced by laser heating.*

Changing the endcap material to Be has a small positive effect with poor laser coupling



1.7×10^{12}
2.1 keV

Endcaps
Al to Be

3.1×10^{12}
2.3 keV

Height
7.5 to 10 mm

Window
3.5 to 1.7 μm

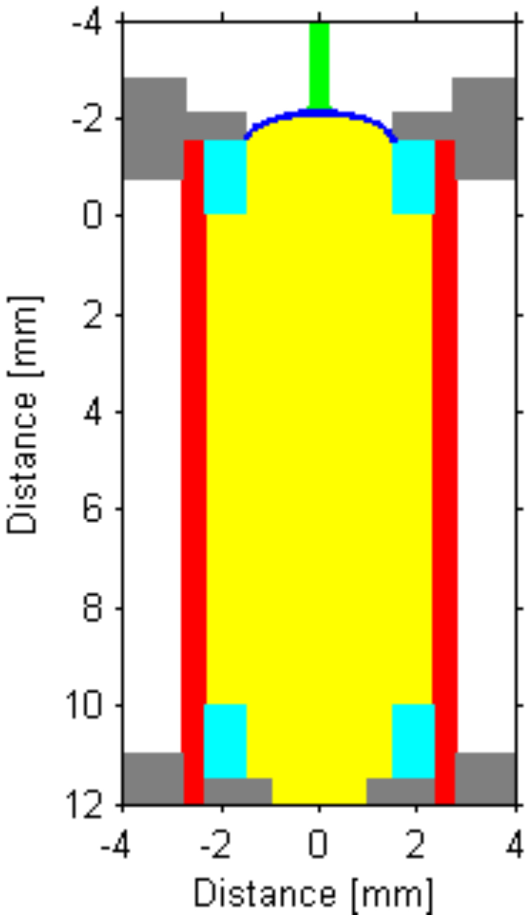
2.5×10^{11}
1.5 keV

Laser
2.5 to 4 kJ

1.1×10^{11}
1.1 keV

Baseline Target Parameters
Window thickness = 3.5 μm
Target height = 7.5 mm
Laser energy = 2.5 kJ
Endcap material = aluminum

Increasing target height increases load inductance, which reduces drive/performance



1.7×10^{12}
2.1 keV

Endcaps
Al to Be

3.1×10^{12}
2.3 keV

Height
7.5 to 10 mm

1.0×10^{12}
1.5 keV

Height
7.5 to 10 mm

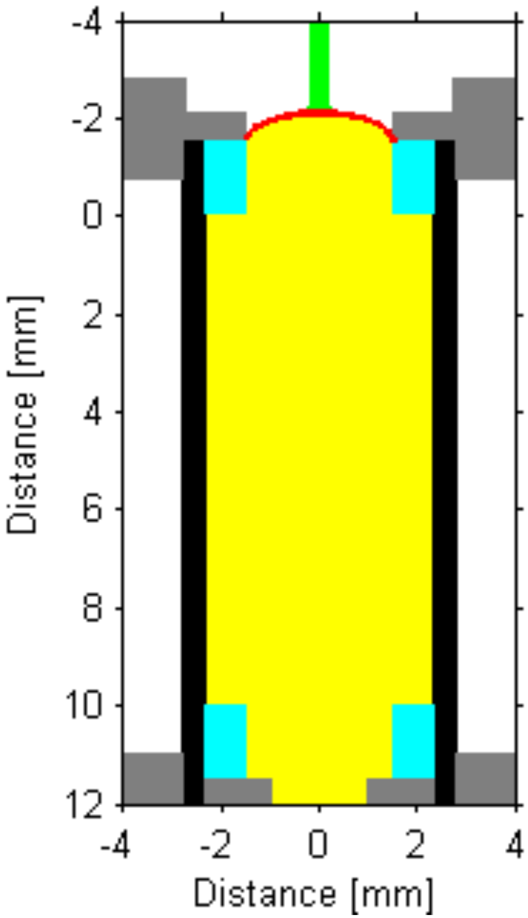
Window
3.5 to 1.7 μm

2.5×10^{11}
1.5 keV

Laser
2.5 to 4 kJ

1.1×10^{11}
1.1 keV

Improving laser coupling with low Z endcaps improves performance



1.7 x 10^{12}
2.1 keV

Endcaps
Al to Be

3.1 x 10^{12}
2.3 keV

Height
7.5 to 10 mm

Height
7.5 to 10 mm

1.0 x 10^{12}
1.5 keV

Window
3.5 to 1.7 μm

Window
3.5 to 1.7 μm

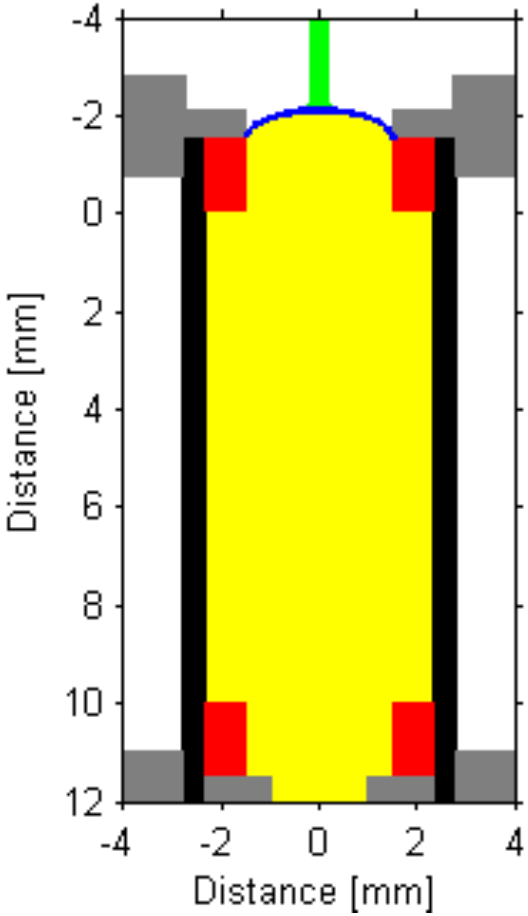
1.1 x 10^{11}
1.1 keV

Laser
2.5 to 4 kJ

2.5 x 10^{11}
1.5 keV

3.2 x 10^{12}
2.2 keV

Equivalently, changing to low Z endcaps with nominal laser coupling improves performance



1.7×10^{12}
2.1 keV

Endcaps
Al to Be

3.1×10^{12}
2.3 keV

Height
7.5 to 10 mm

1.0×10^{12}
1.5 keV

Window
3.5 to 1.7 μm

Height
7.5 to 10 mm

Window
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1.1×10^{11}
1.1 keV

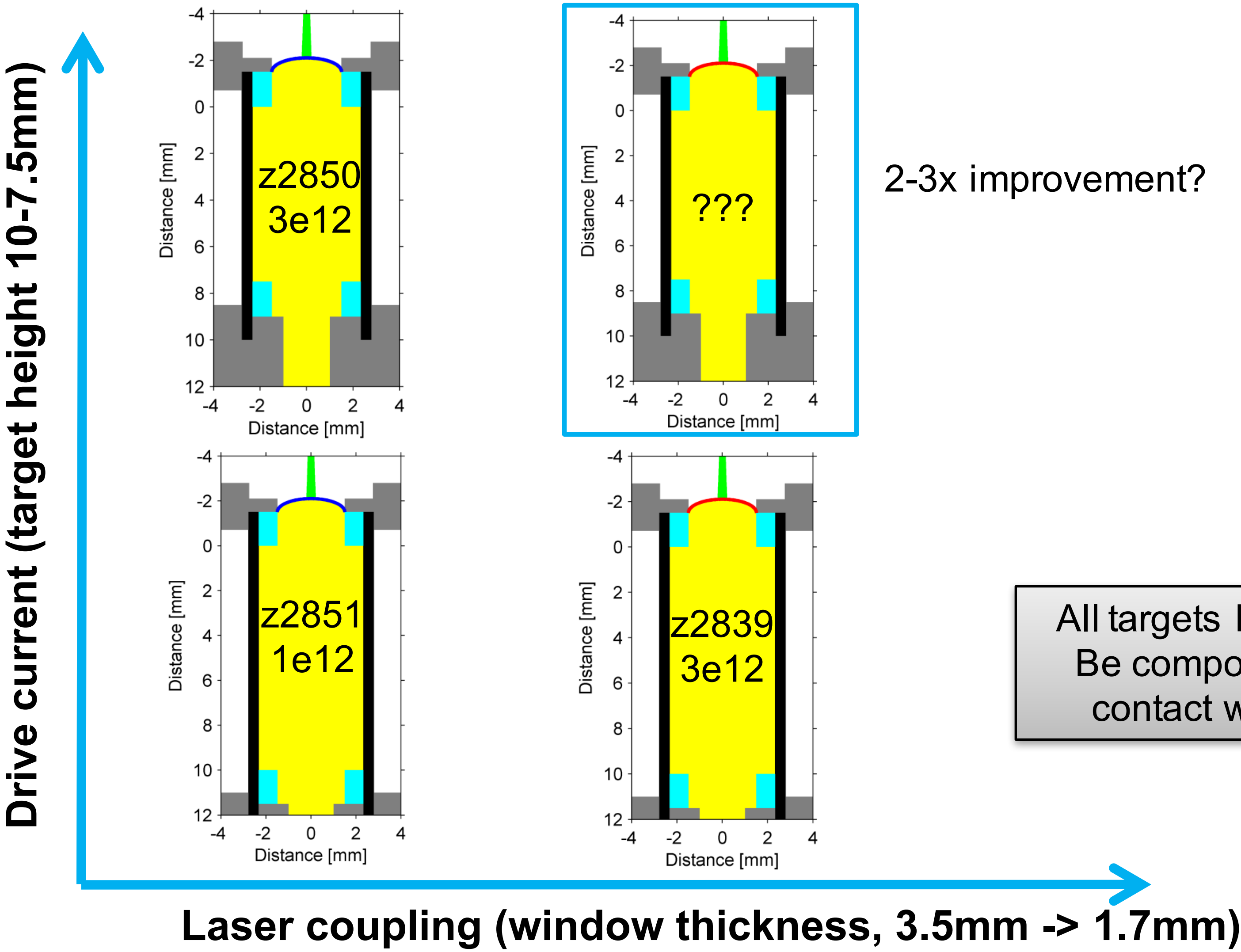
Laser
2.5 to 4 kJ

2.5×10^{11}
1.5 keV

Endcaps
Al to Be

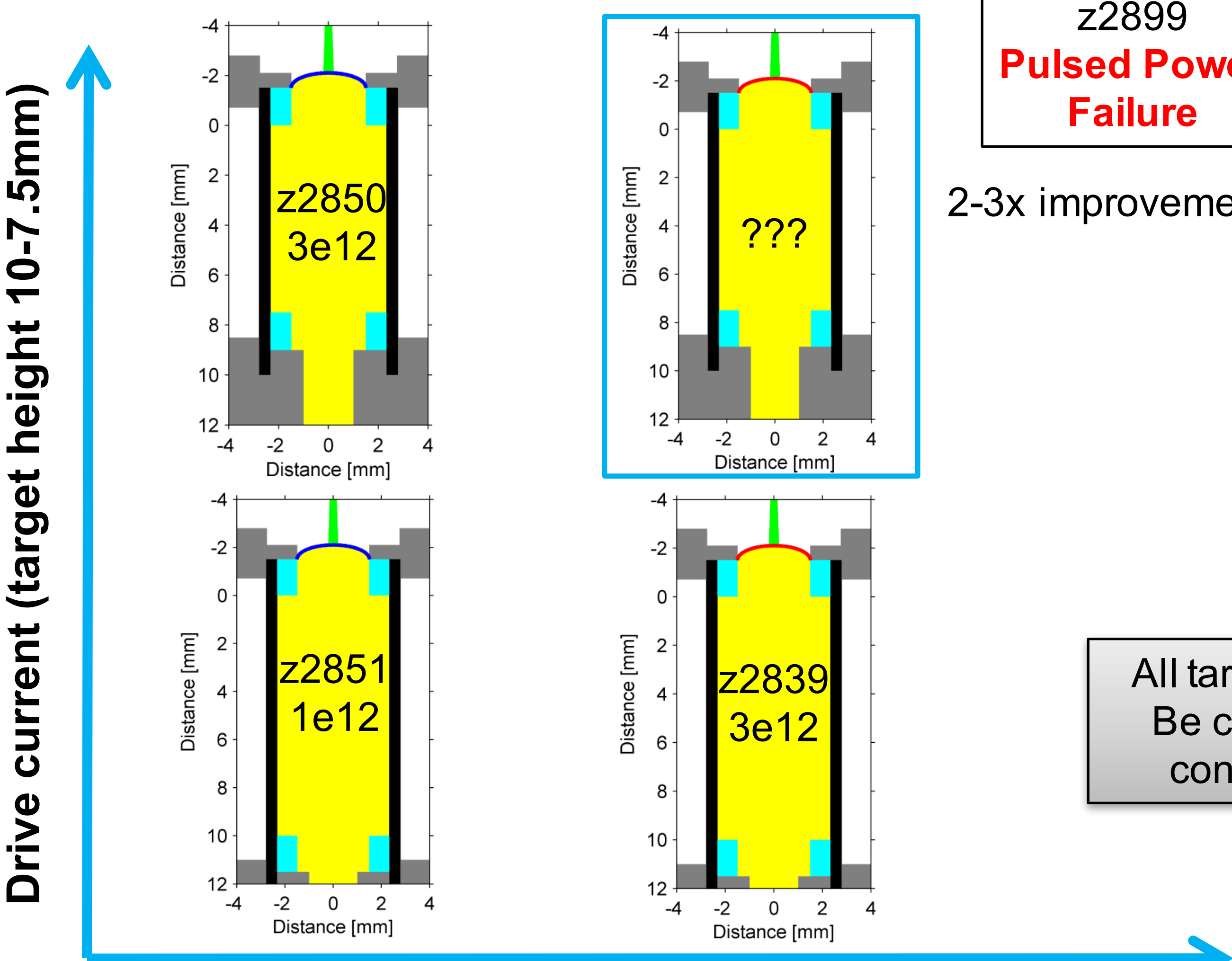
3.2×10^{12}
2.2 keV

Our best performing targets appear to scale with drive current and energy coupling



All targets have only Be components in contact with fuel

Our best performing targets appear to scale with drive current and energy coupling



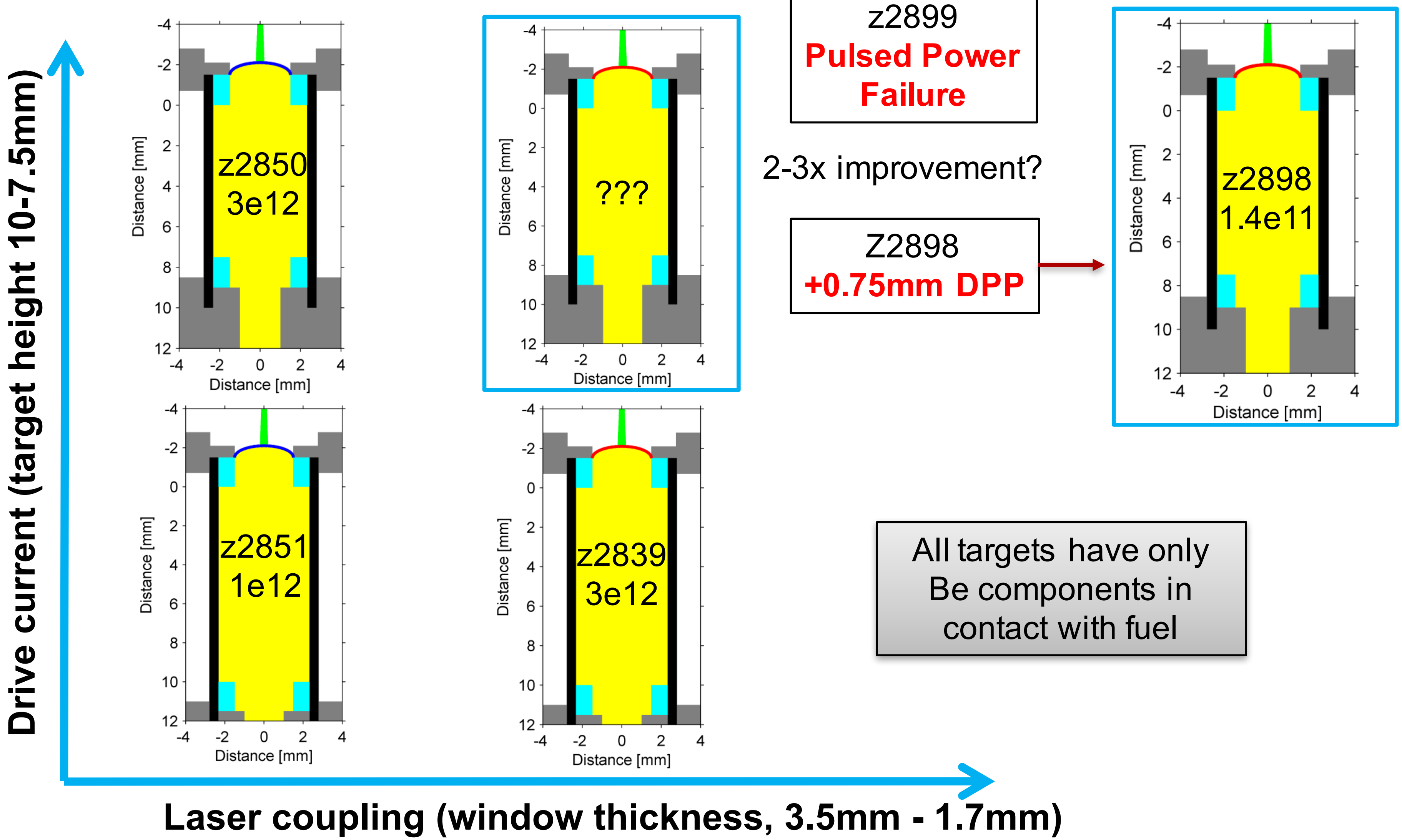
z2899
Pulsed Power Failure

2-3x improvement?

All targets have only Be components in contact with fuel

Laser coupling (window thickness, 3.5mm -> 1.7mm)

The configuration of our first phase plate test was largely driven by empirical progress with the unconditioned beam



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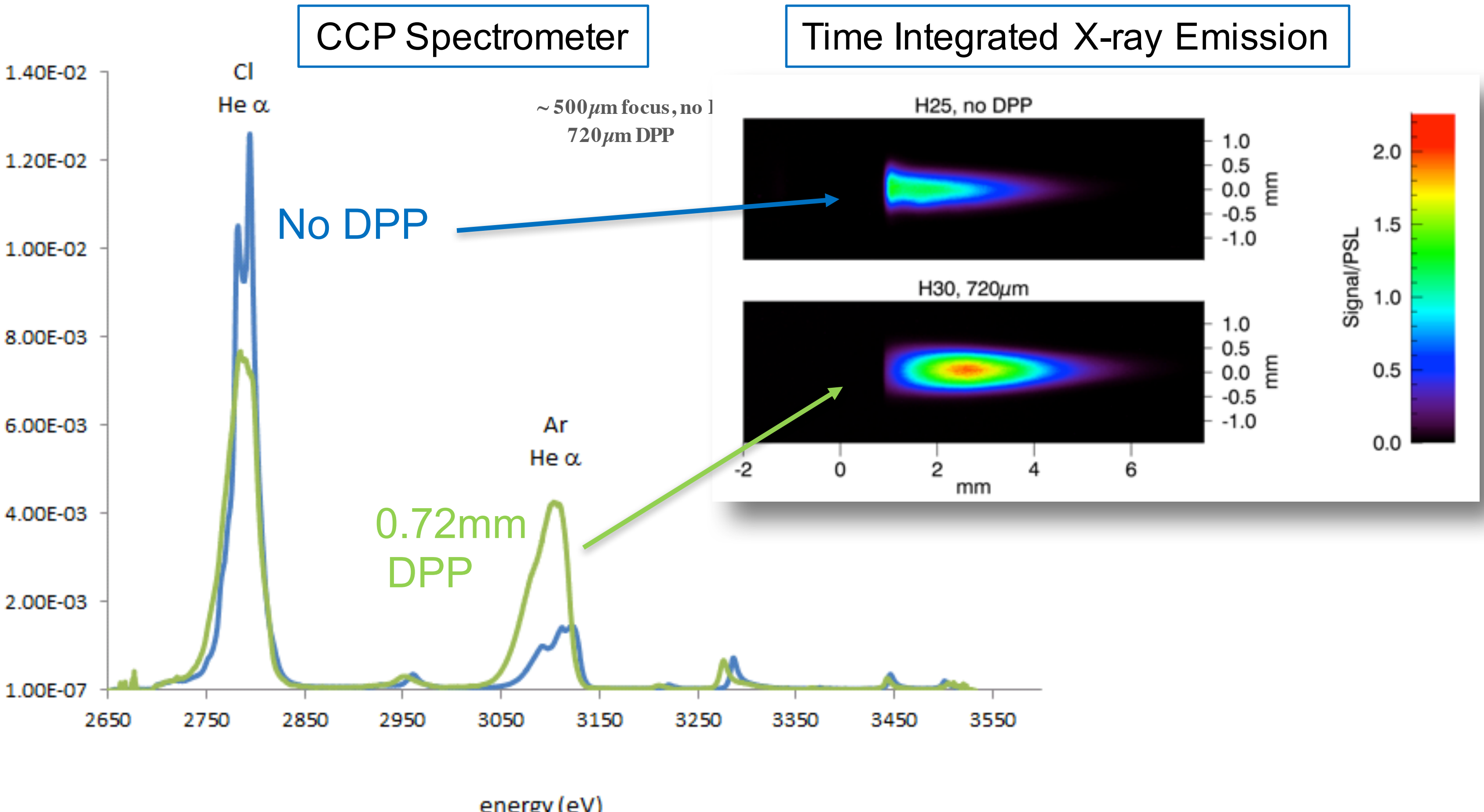
We are investigating laser preheating at several different facilities, each with different goals

- **ZBL** (AAC talks: Geissel, Schwarz, Posters: Schmitt, Bliss)
  - Magnetization studies (Z)
  - Qualification of preheat platform (Z)
  - Window transmission study (PECOS)
  - Optical blast wave interaction studies (PECOS)
  - 2ω LPI and beam conditioning tests (PECOS)
- **OMEGA-EP** (AAC talks: Harvey-Thompson, Nagayama)
  - Characterize beam propagation, energy deposition, and laser induced mix as a function of initial density, laser power, and energy
- **OMEGA** (AAC talks: Davies, Barnak)
  - Development of $1/10^{th}$ scale integrated MagLIF platform
- **NIF** (AAC talks: Pollock, Strozzi)
  - Study scaling issues for preheating MagLIF targets with up to 30kJ

ZBL experiments with phase plates show increased energy coupling to the fuel and less x-ray emission from Cl doped window

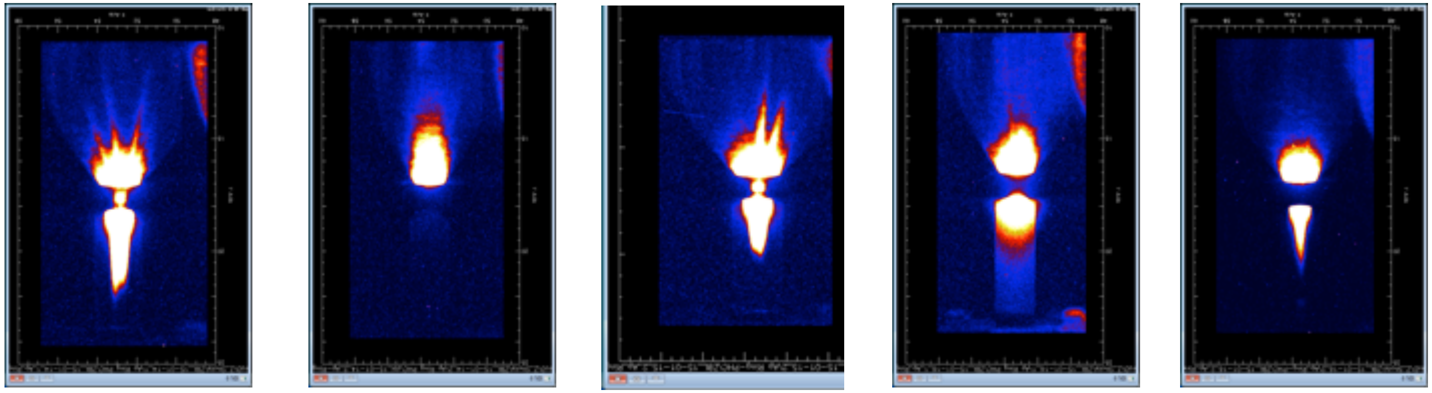


Acknowledgement:
Stephanie Hansen, data analysis

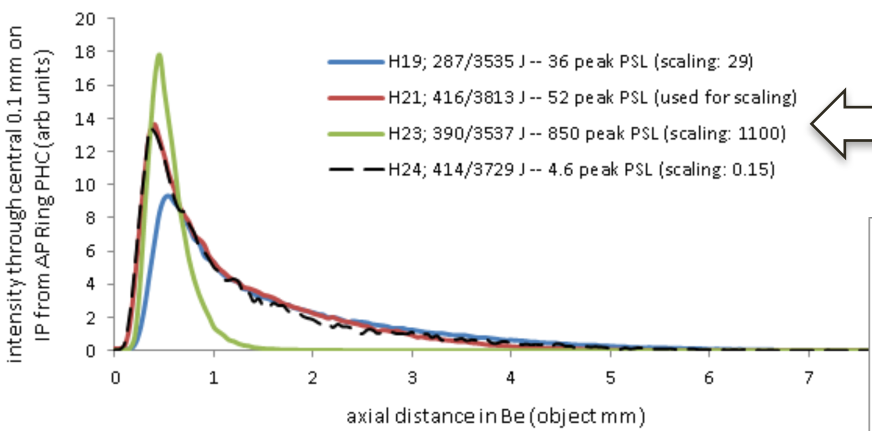
60 psi D_2 with 0.1% Ar-dopant

Laser only experiments on Z (with ~1.8mm DPP) **suggests *significant* window mix**

All pinhole images have similar intensities above washer

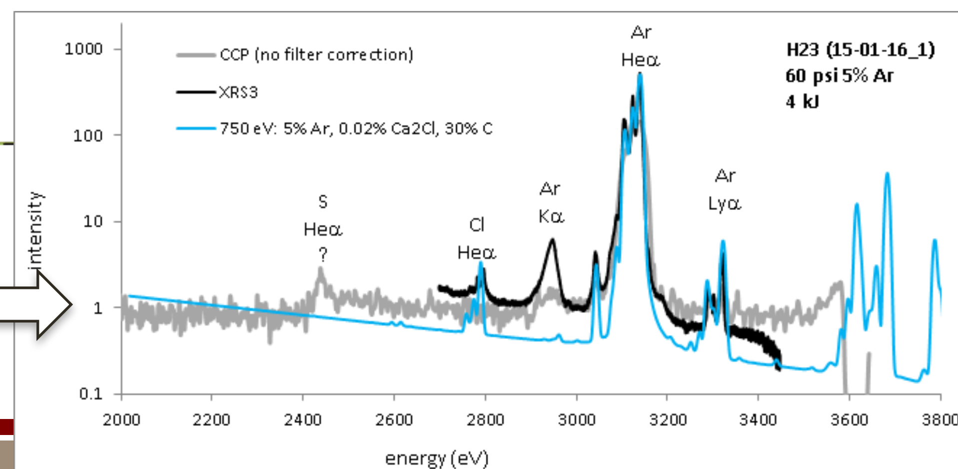


H19 45 psi, 0.5% Ar | H20 50 psi, Pure Ne | H22 60 psi, 0.5% Ar | H23 60 psi , 5% Ar | H24 60 psi, pure D2

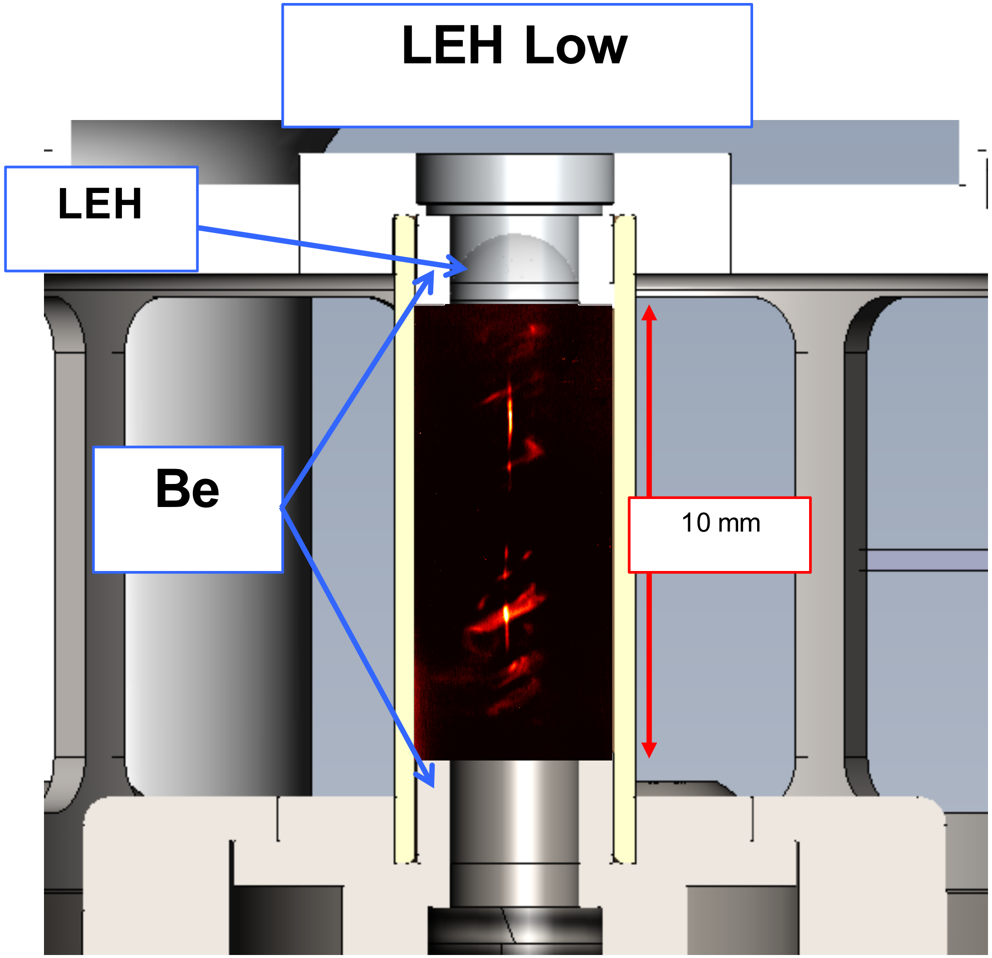


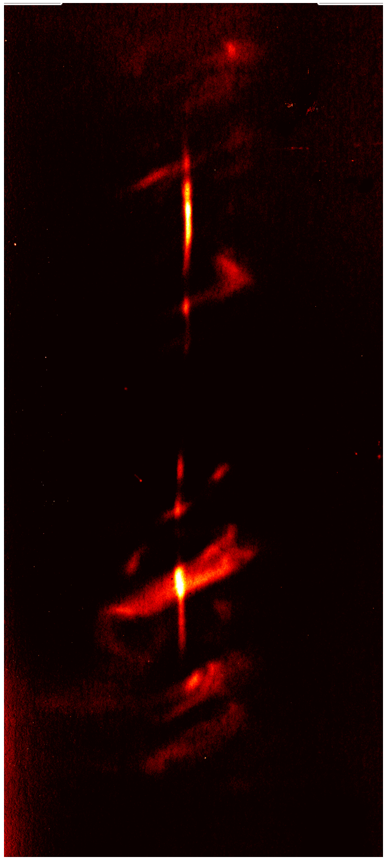
Axial lineouts below washer show similar profiles for low dopant fractions, with intensity scaling that suggests 10% carbon mix in pure D2 case (H22)

XRS3 spectra indicate fill temperatures of 0.6 – 0.8 keV, small (~0.02%) Cl mix fractions, and significant (>20%) low-Z mix



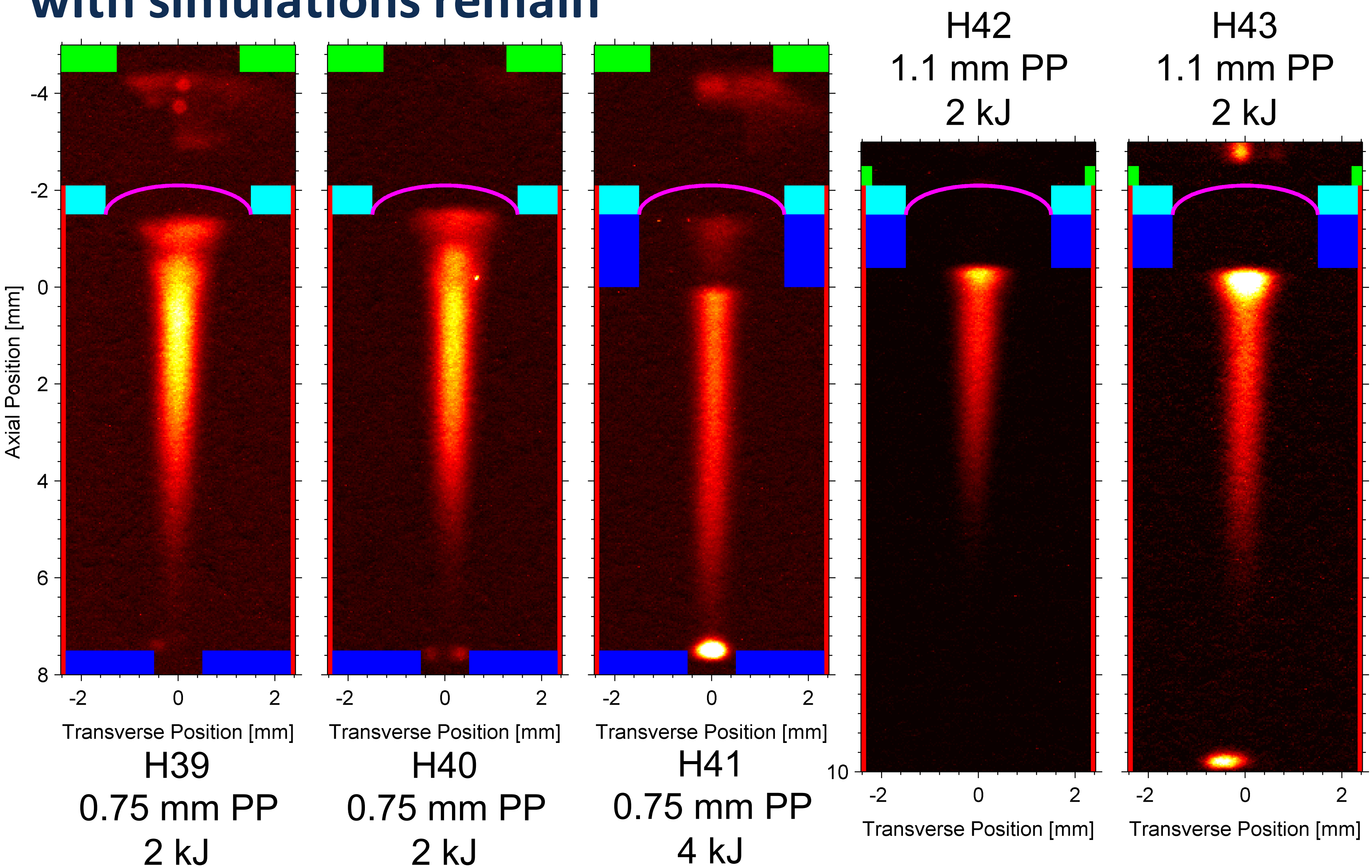
Lowering the LEH window also significantly reduces performance





Y_{dd}=3.8e10 (~85x reduction)

Even with phase plates, qualitative discrepancies with simulations remain



All use D_2 + 0.1% atomic Ar; H39-H42 at 60 PSI; H43 at 45 PSI

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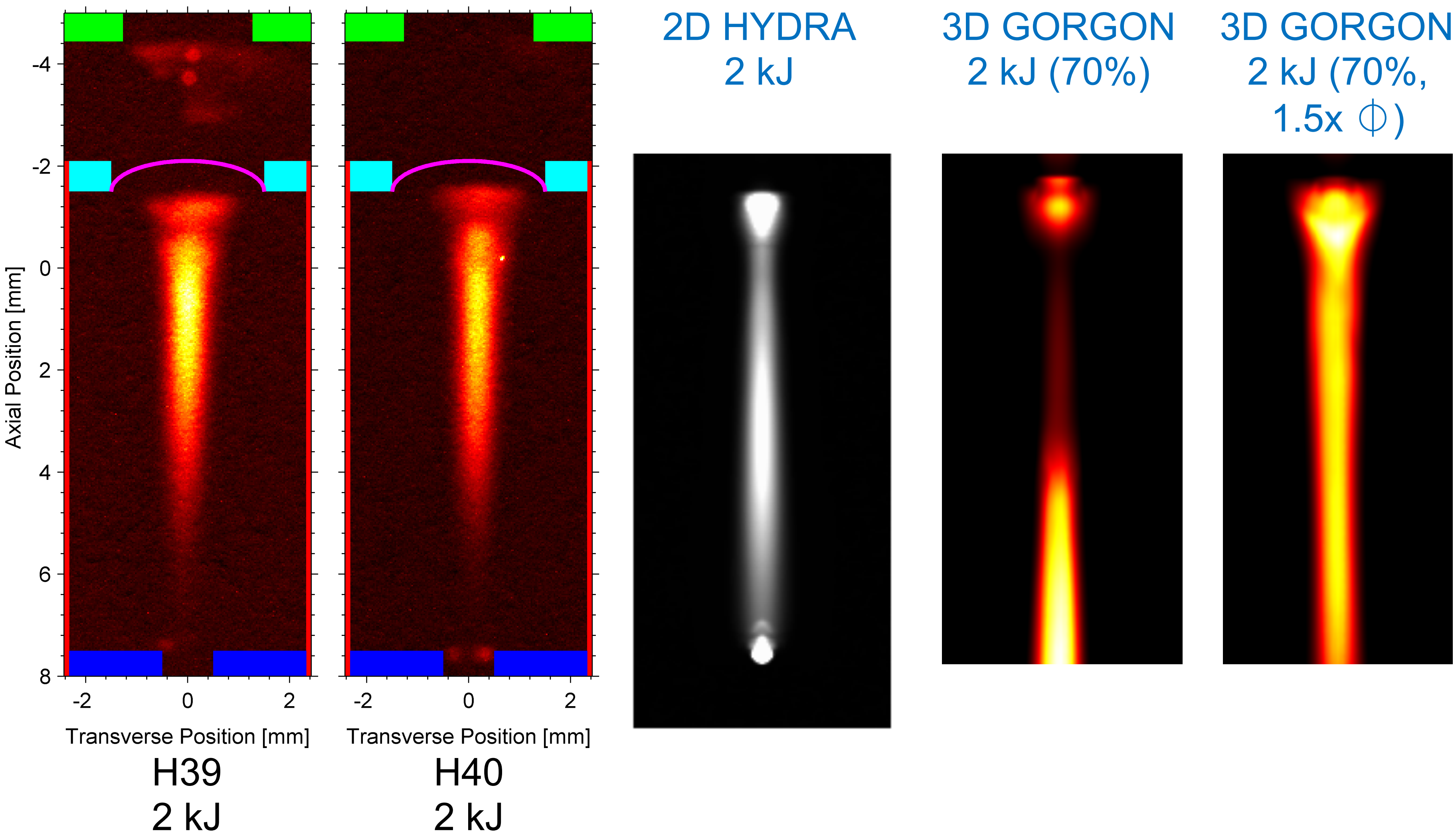

All use D_2 + 0.1% atomic Ar; H39-H42 at 60 PSI; H43 at 45 PSI

We are addressing simulation discrepancies in two ways

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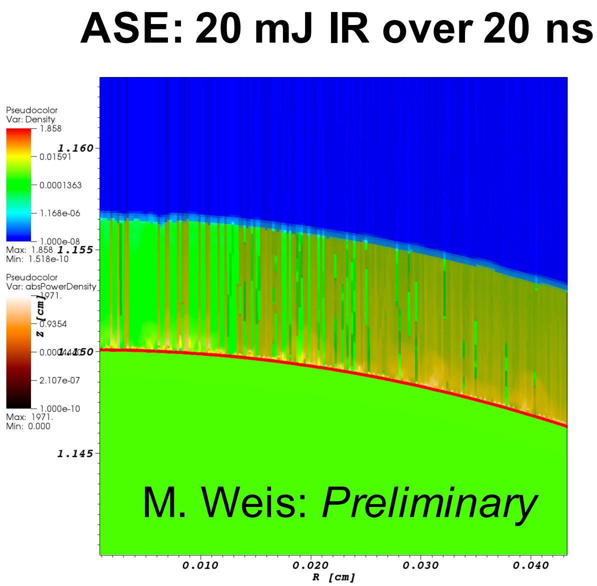
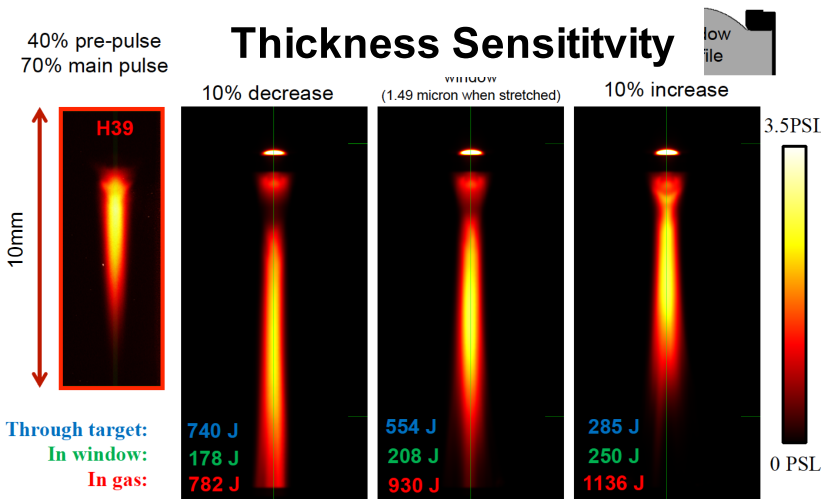
- How well do we really know out initial conditions?
  - Laser focus, delivered energy, etc.
  - Could IR Amplified Spontaneous Emission (ASE) be pre-disassembling LEH window?
  - What is level of laser scatter due to LPI? (2ω, 2.5e14 W/cm^2)
  - Does firing the magnetic field coils change initial state of window or target?
  - Is the laser interacting with the focusing target?
- Are the physics models in our hydrodynamic codes sufficient to model laser heating?





We are currently working on a plan to develop a new baseline MagLIF platform using a DPP

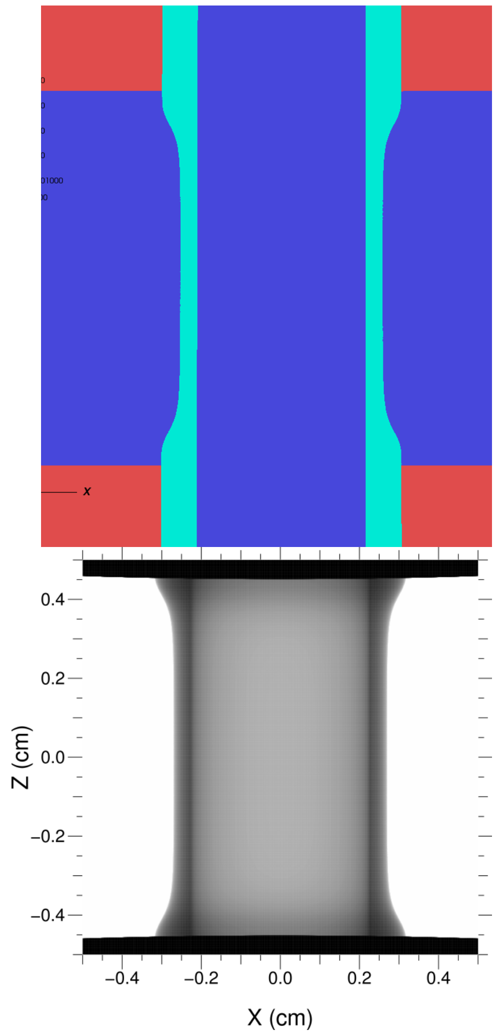
- **Goal:** Assess integrated MagLIF performance using one or more conditioned-beam laser preheat platforms at a fixed total energy deposited into deuterium fuel to the present 2kJ unconditioned beam. (June-July)
- **Target:** (Z2839-like) 10 mm long, AR6 Be liner with Be cushions, 57 psi DD fill, and a 1.5 um LEH window
- **Approach**

   1. Use Pecos experiments to develop conditioned beam laser platforms that match the transmission through the LEH with the unconditioned beam and reasonably match blast-wave evolution (depth, radial velocity). --- minimize mix with no pre-pulse
   2. Simulate these Pecos experiments to verify understanding.
   3. Simulate the integrated MagLIF target performance using these conditioned beam platforms.

We are pursuing several areas of target design improvements

- Minimize mix
  - Thin windows (cryo)
  - Increase window standoff
  - Increase diameter of LEH
  - All low-Z components, ICE layers
  - Larger beam dump
  - Ramped pulse shapes
- Increase fuel density
- Minimize target inductance (increase current)
- Higher aspect ratio liners

Cryogenic target



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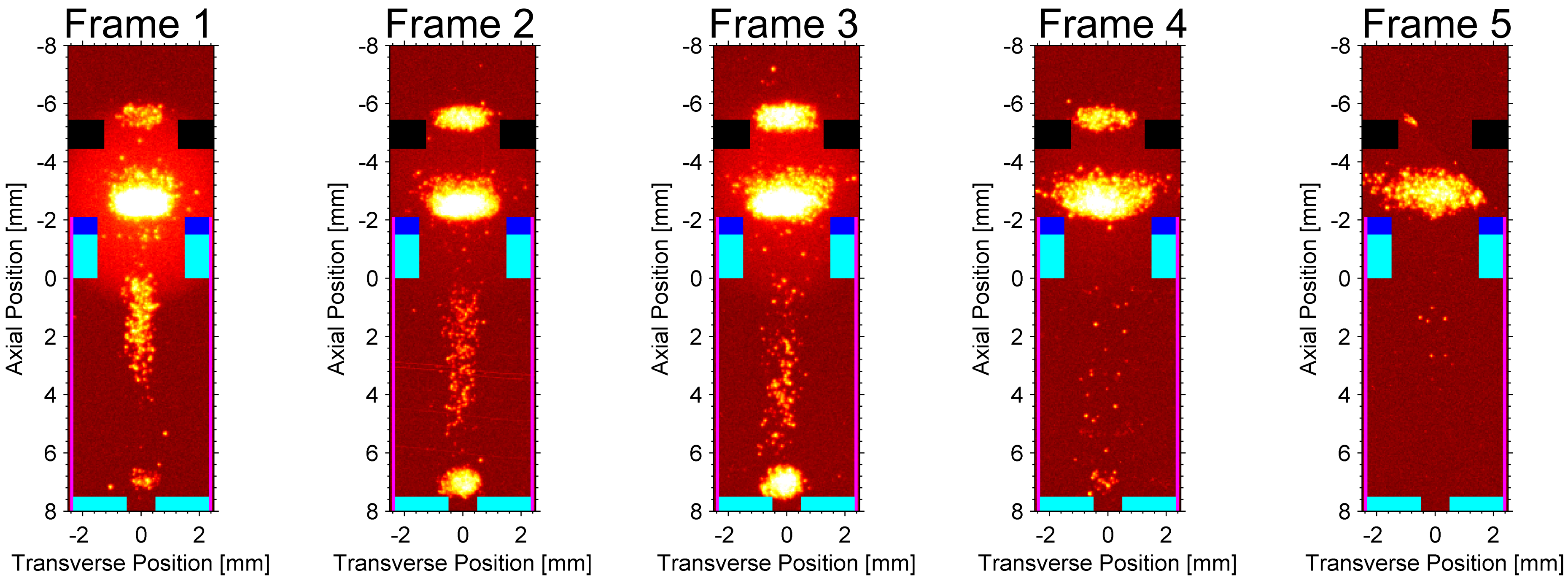
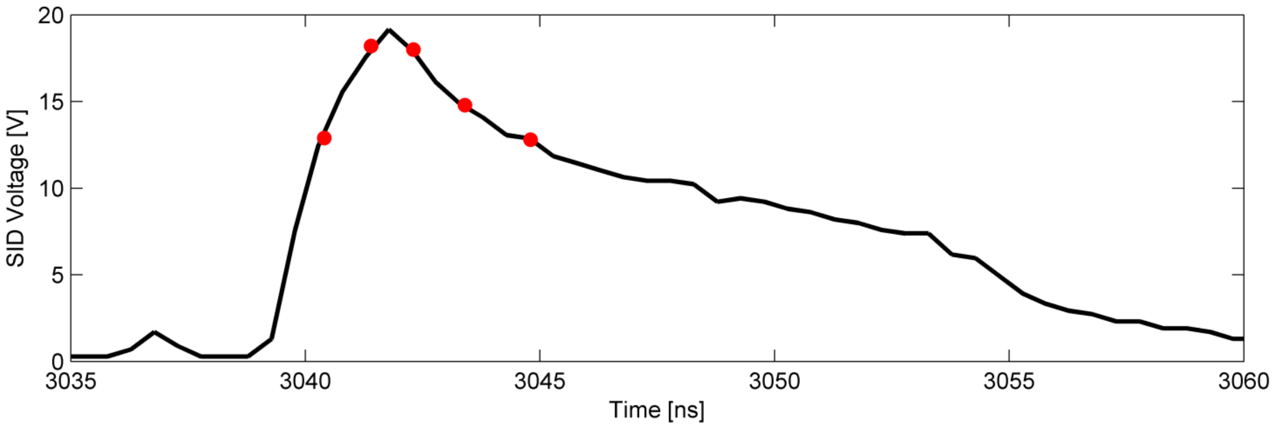
Backups

H41 MLM images





The SID signals may be responding to the window emission, which persists longer in the MLM images than Ar emission

Magnetized Liner Inertial Fusion (MagLIF)

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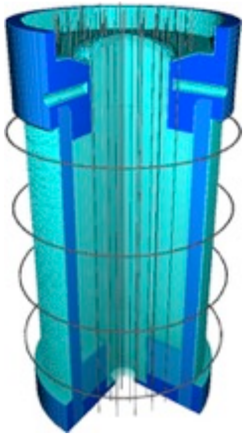
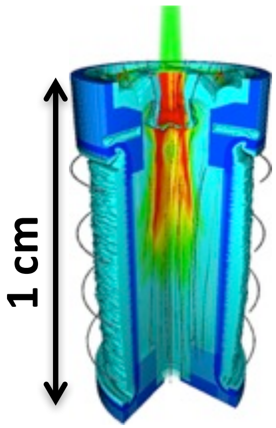


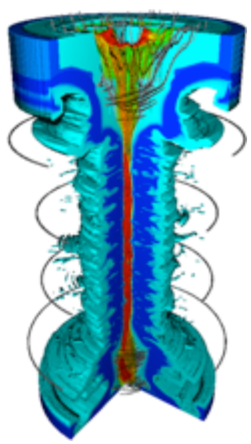
Initialize axial magnetic field (B_0 = 10-30 T)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Flux compression increases field to kT
- Fusion products magnetized → α particles become trapped in field



Laser heating of fuel (E_L = 2-4 kJ)

- Initial average fuel temperature 150-200 eV → 10 keV at compression
- Reduces compression requirements (final size and velocity)
- Coupling of laser to plasma in an important science issue



Magnetic compression of fuel

- 70-100 km/s, quasi-adiabatic fuel compression
- Low Aspect liners ($r/\Delta r \approx 6$) are robust to hydrodynamic instabilities
- Significantly lower pressure/density than NIF ICF

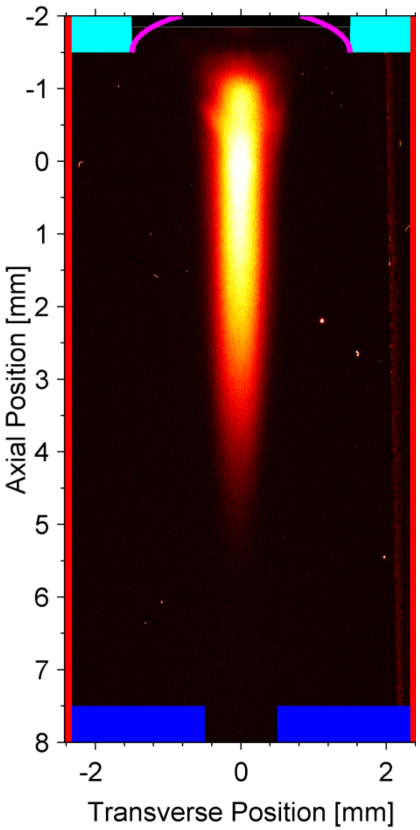
S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz & R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014)

Changes to experimental parameters have explainable impacts on target performance

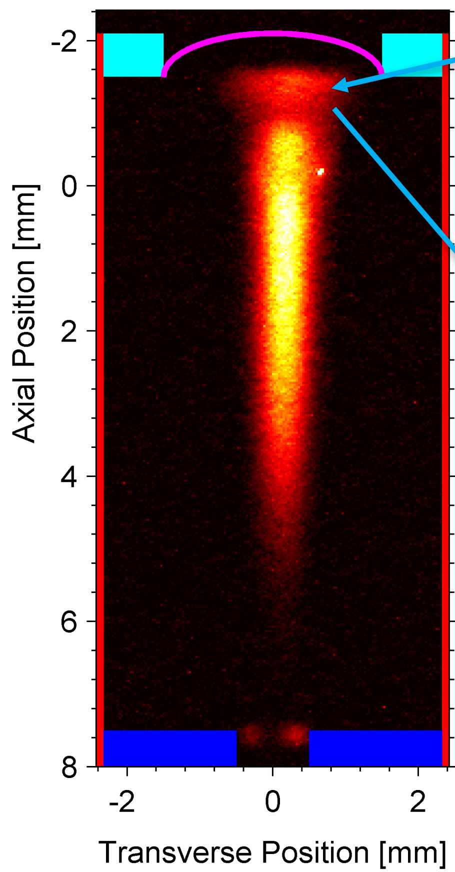
Change to experiment	Impact of change	Explanation of impact
Endcap material Aluminum → Beryllium **3.5 μm window**	• 1.8x increase in yield	• Thick window = low preheat = low mix • Endcap material not critical
Endcap material Aluminum → Beryllium **1.7 μm window**	• 13x increase in yield • 1.5x increase in temp	• Thin window = nominal preheat = moderate mix • Endcap material is critical
Laser energy 2.5 → 4 kJ **1.7 μm window** **Aluminum endcaps**	• 2.3x decrease in yield • Weak emission from top of stagnation column	• Increased preheat increases mix, important with Al endcaps
Target height 7.5 → 10 mm	• 3x decrease in yield • Delayed stagnation	• Decreased drive current = lower implosion velocity = lower temperature

Pre-pulse signatures are evident in time integrated data

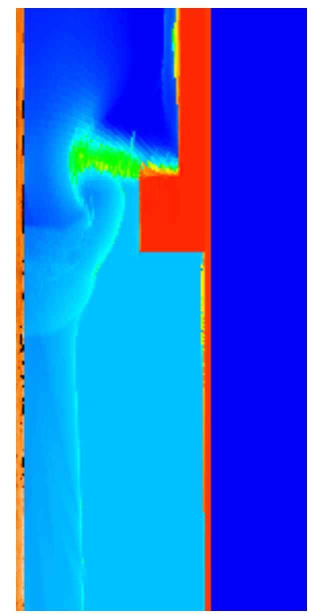
Crystal imager (3keV+6keV



Pinhole camera



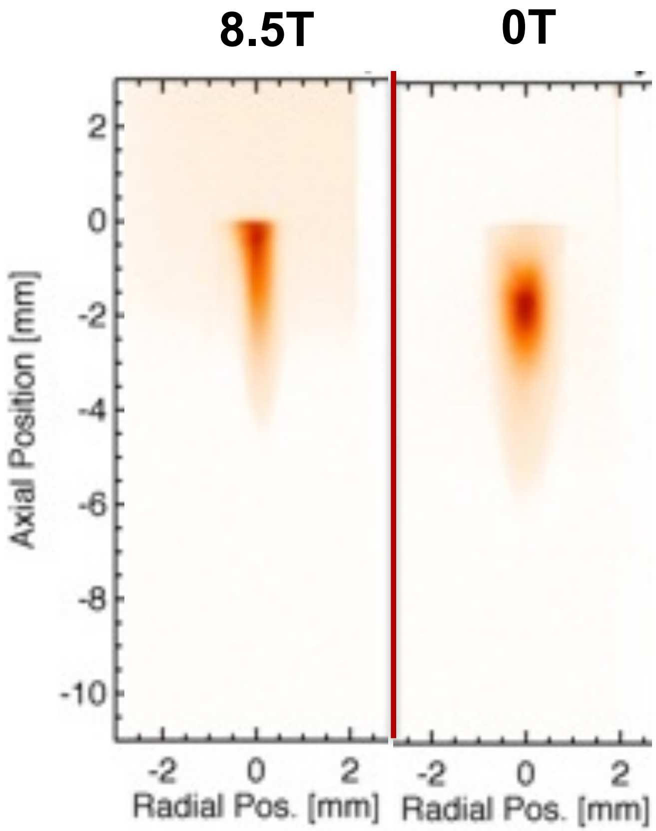
- Window or prepulse shock emission?
- Emission in this region is not from argon.
- Brighter for larger DPP and lower gas pressures

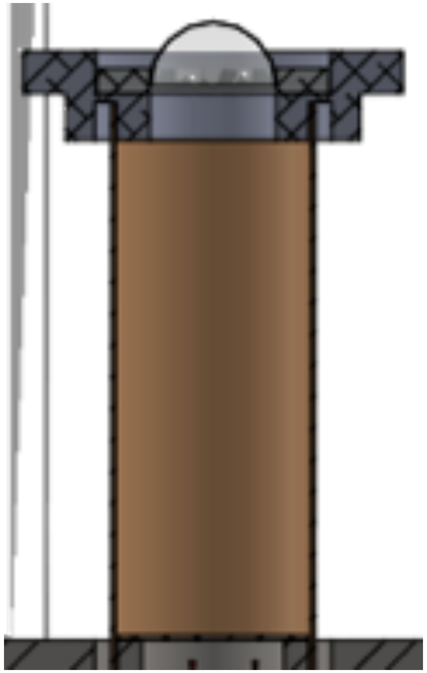


2D HYDRA Simulation

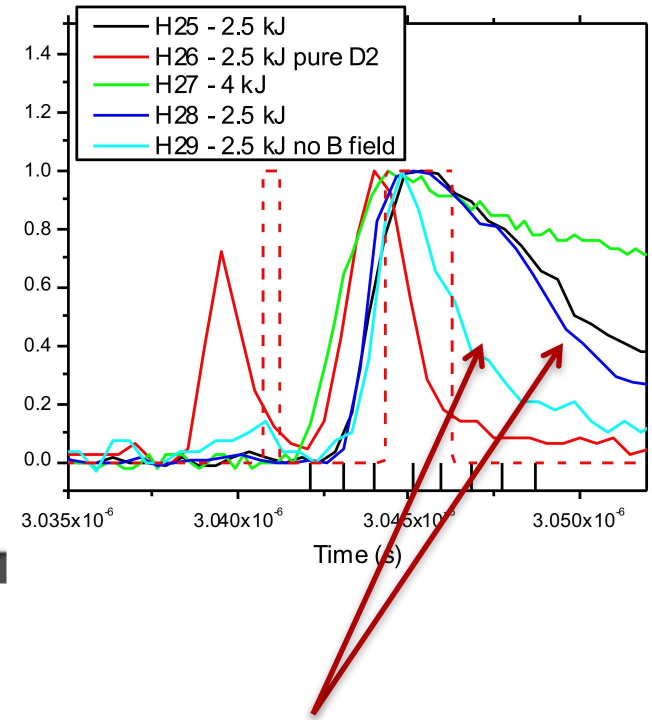
Emission is slightly wider than with 0.75 mm phase plate

We have observed significant magnetization effects in ZBL experiments





Normalized X-ray emission history

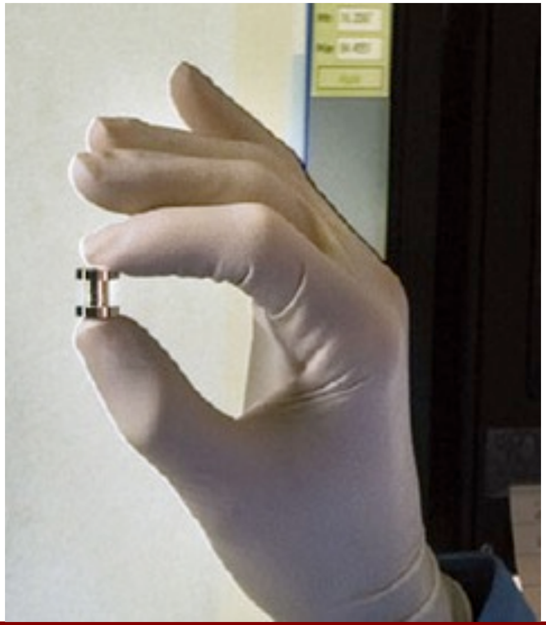


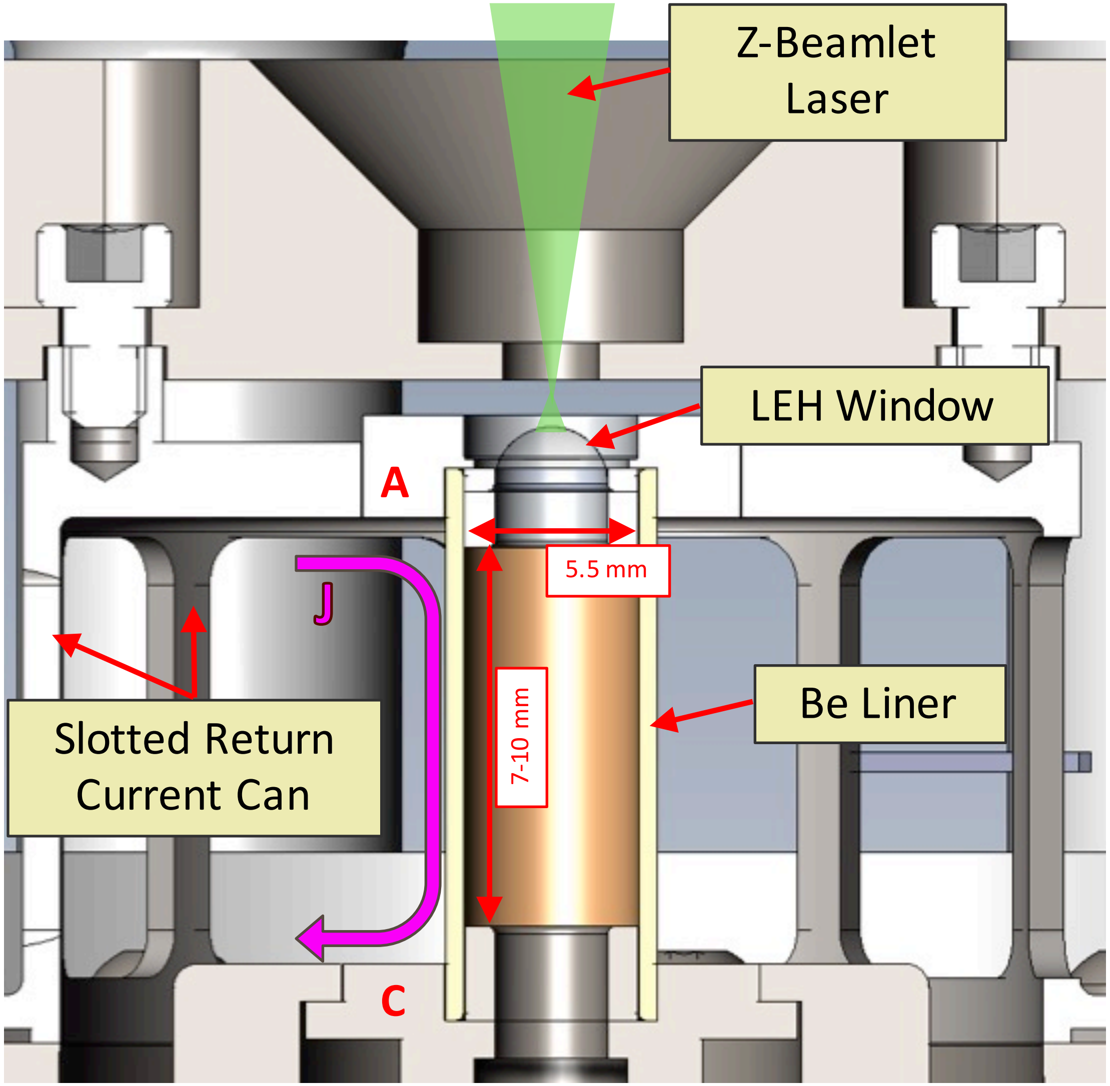
H28 vs H29
2.5kJ, **No DPP**

Significant increase in plasma Lifetime with 8.5 T

Anatomy of a MagLIF Target

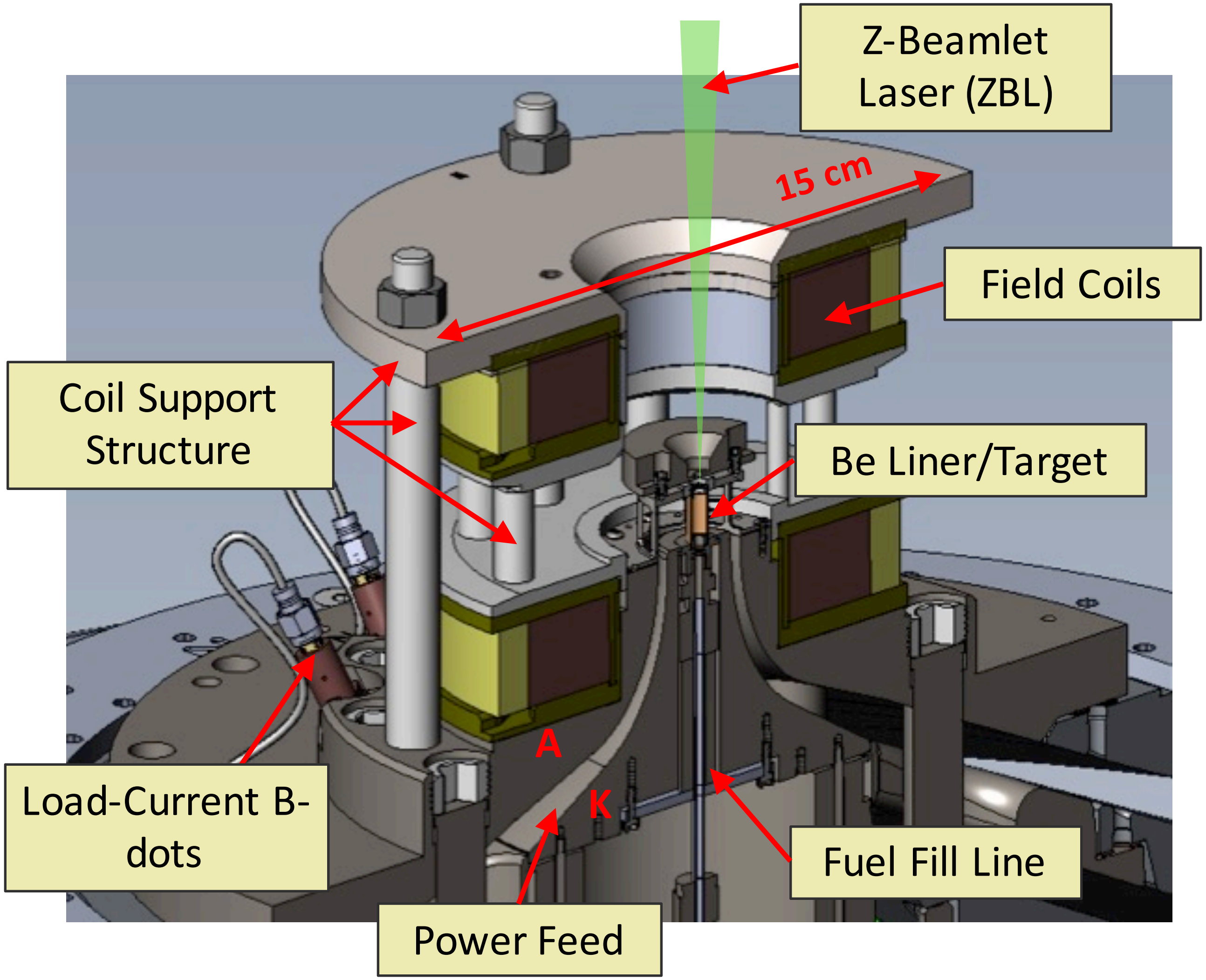
- **Be Liner**: OD = 5.63 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window**: 1-3 µm thick plastic window. Supports 60 PSI pure D2 gas fill.
- **Return Can:** Slotted for diagnostic access



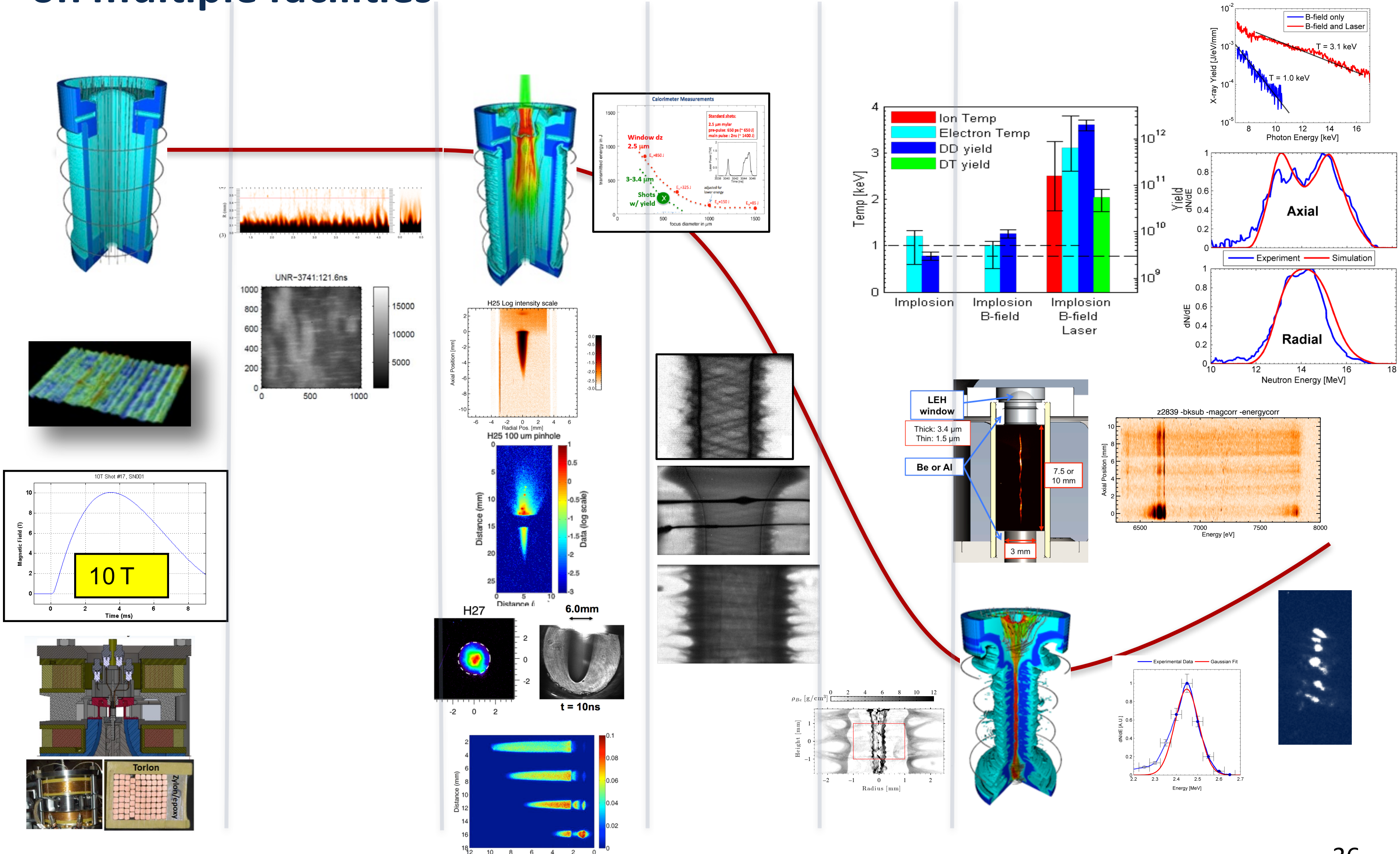


Anatomy of a MagLIF Experiment

- **Field Coils**: Helmholtz-like coil pair, 10-30 T axial field w/ ≈3 ms rise time
- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse
- **Power Feed**: Up to 24 MA (typical ≈18 MA) in 120 ns



We are collecting data on all phases of MagLIF implosions, on multiple facilities

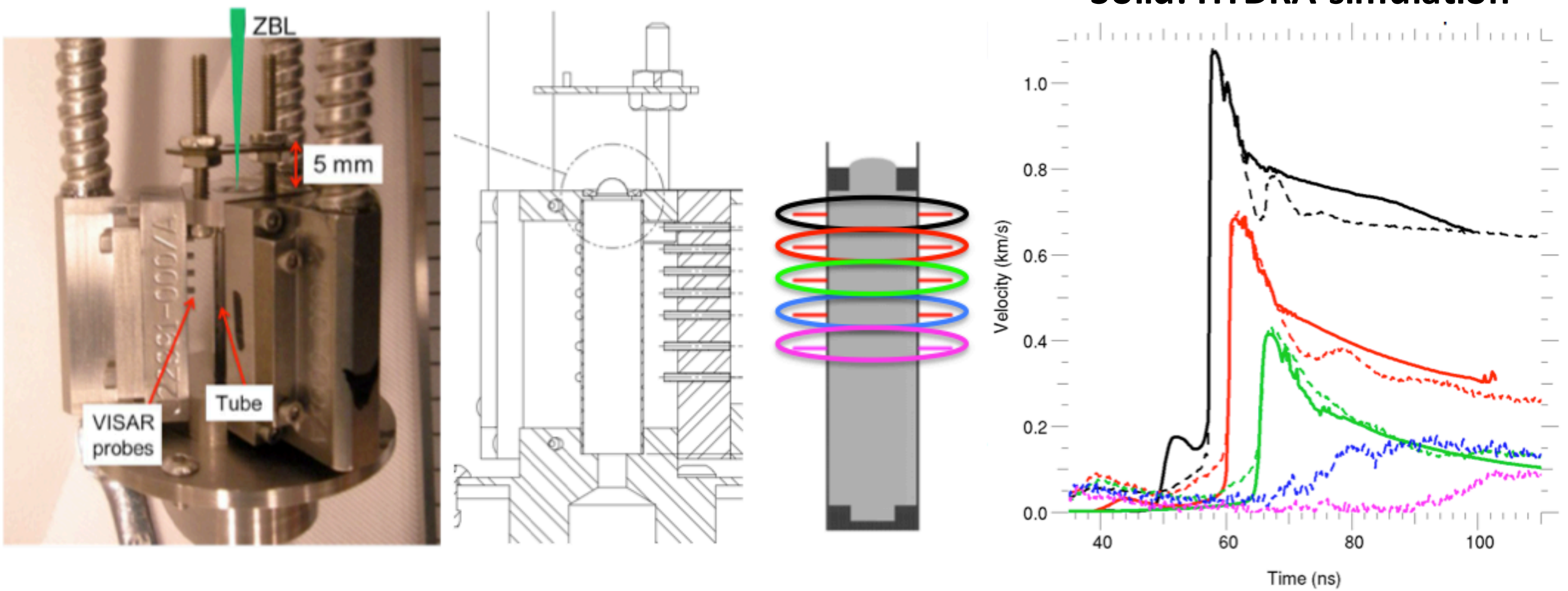


Our current focus is on better understanding of fuel preheating and mix

Four sets of data imply low levels of preheat.

Data set #1: Blastwave measurements via VISAR

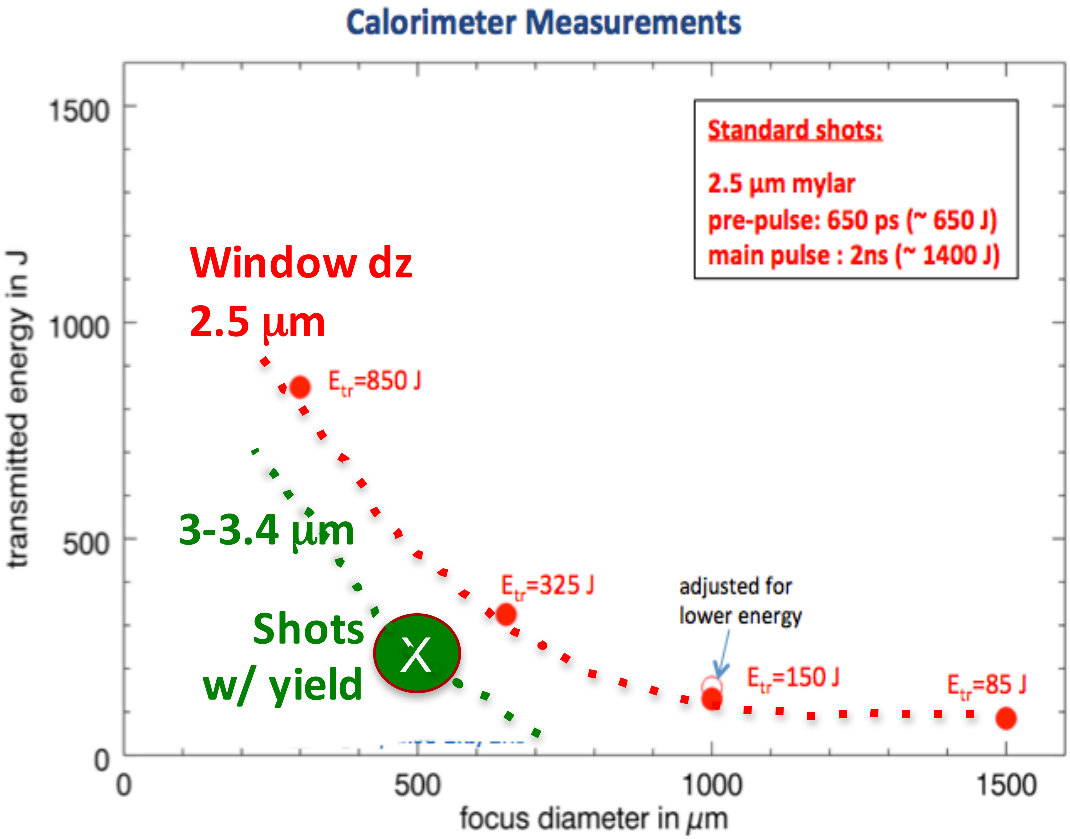
Dashed: Data
Solid: HYDRA simulation

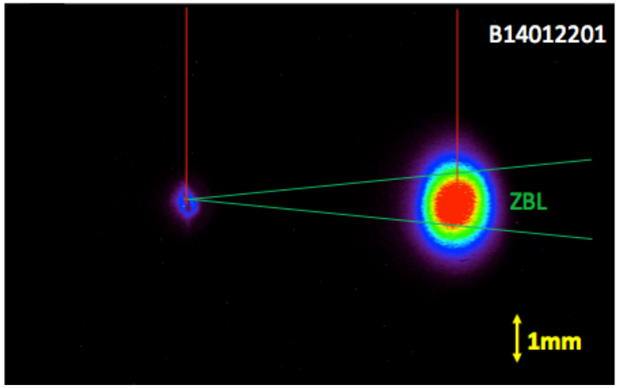


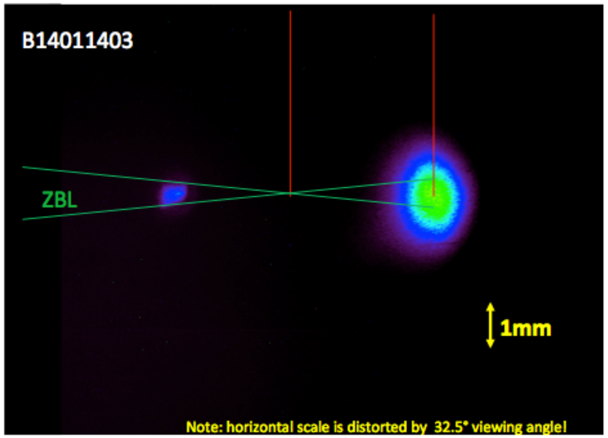
Inferred: 330 J or less coupled to the gas (of ~2.8 kJ)

Four sets of data imply low levels of preheat.

Data set #2: Calorimeter measurements







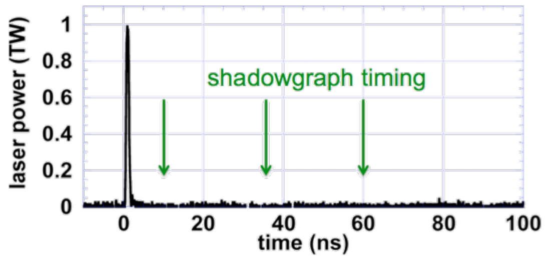
Inferred: ~200-300 J coupled through 3-3.4 μm foils

Four sets of data imply low levels of preheat.

Data set #3: Shadowgraphy of blastwave (~600 J*)

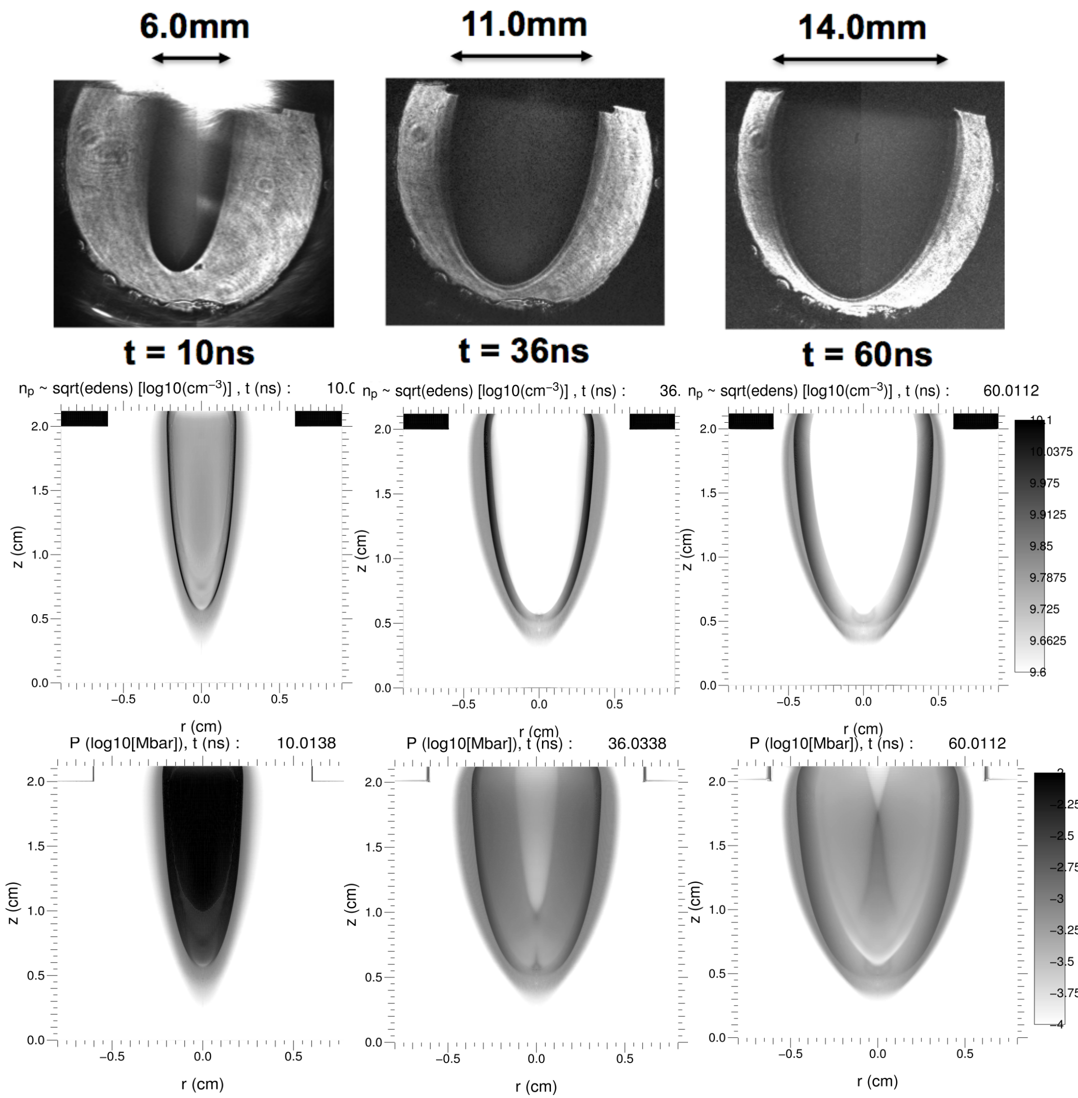
Shadowgraph measurements
Ne 250 Torr gas-cell shot, 10/6/2014

ZBL: 1.8kJ/2ns, 300J prepulse, 1mm dia. focus
Target: scale-2 gas cell, 1μm-thick Mylar LEH, 250 Torr neon gas fill



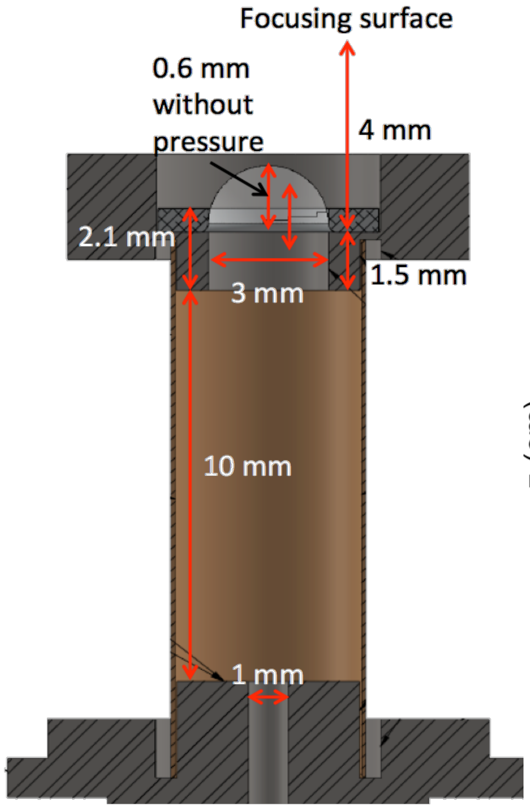
Shadowgraphs appear to measure the plasma's index of refraction $n \sim n_e^{0.5}$, which stays ~constant and captures shock and fuzzy edge radiation feature (whereas ρ, T_e, etc., vary and do not always capture features).

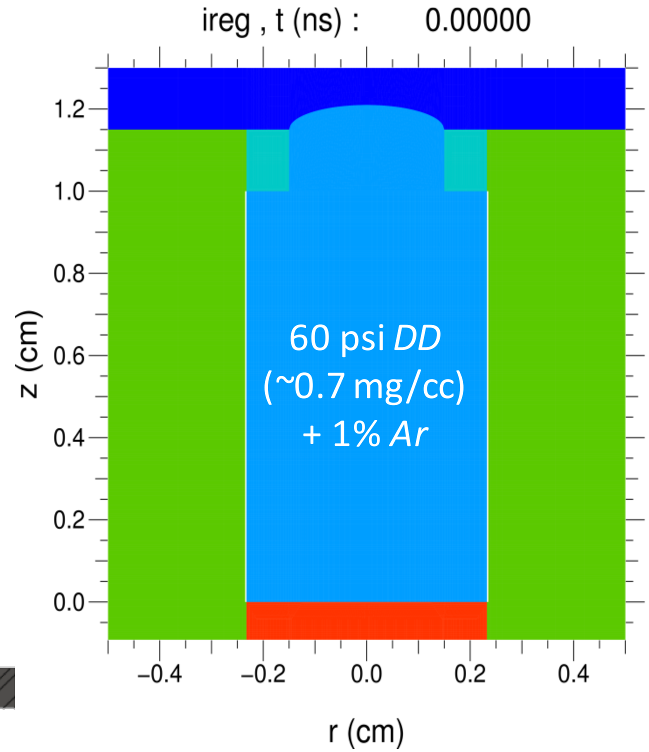
The $n_e^{0.5}$ profile tracks the plasma pressure very well, so the shadowgraphs are indeed measuring the laser absorption (the edge of where the plasma is hot).

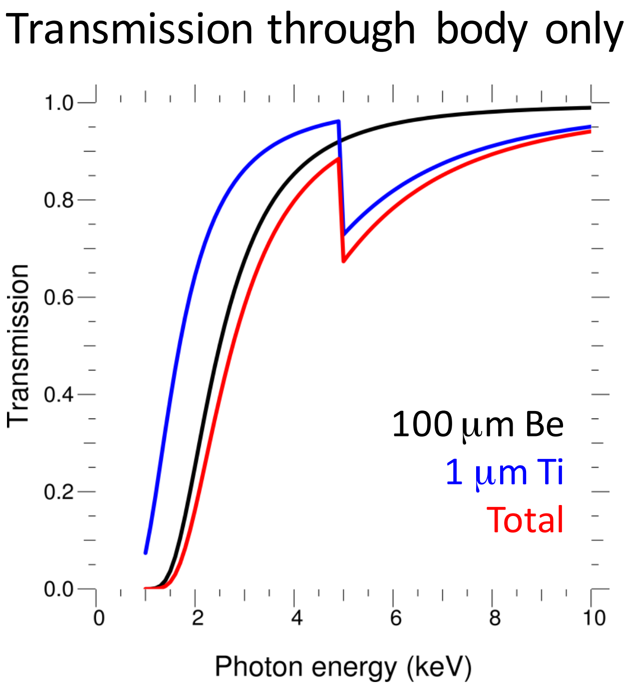


Four sets of data imply low levels of preheat.

Data set #4: Laser with B_z shots in Z chamber





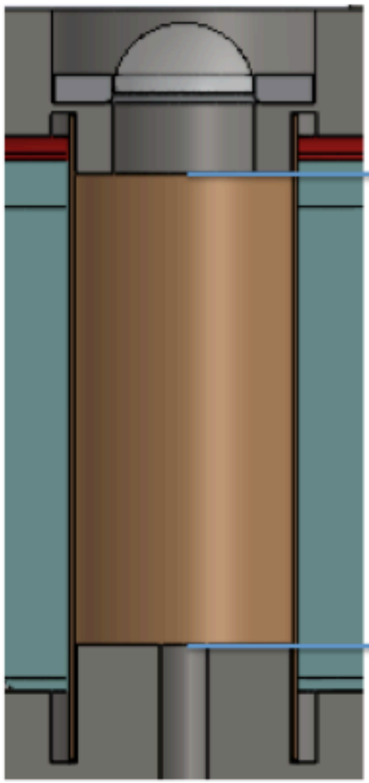


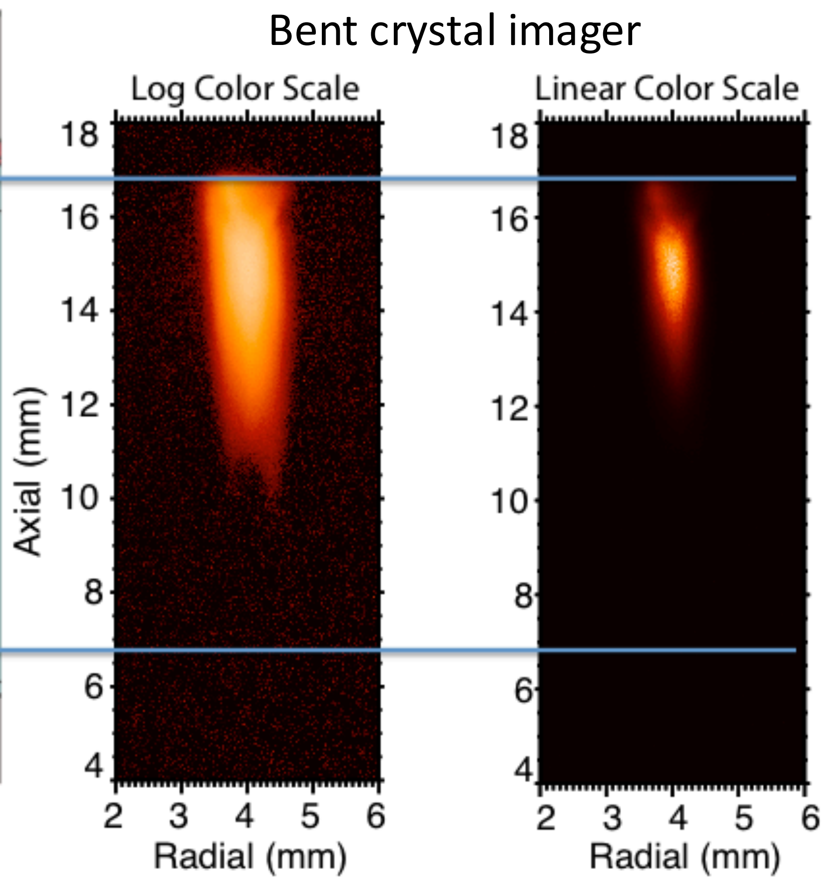
- B_z = 9.8 T
- 1.89 μm polyimide stretched to 1.55 μm
- 100 μm thick *Be* liner + 1 μm thick *Ti* foil
- *KI* solution on top SS endcap
- 1 μm thick *V* foil + $CaCl_2$ solution on *Al* bottom endcap

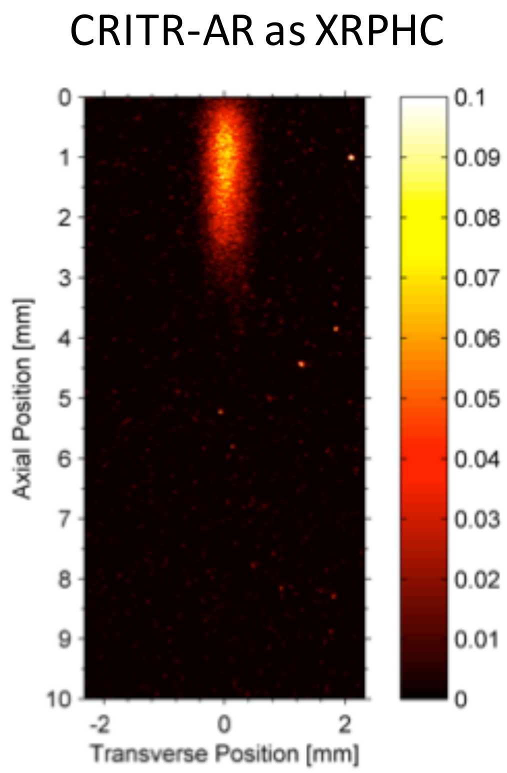
- E_{las} = 497 J (pre) + 2405 J (main)
- no phase plate
- D_{las} ~450-550 μm on window (guess)

Two separate diagnostics confirmed heating

Inferred peak T_e~500 eV (equilibration value lower)







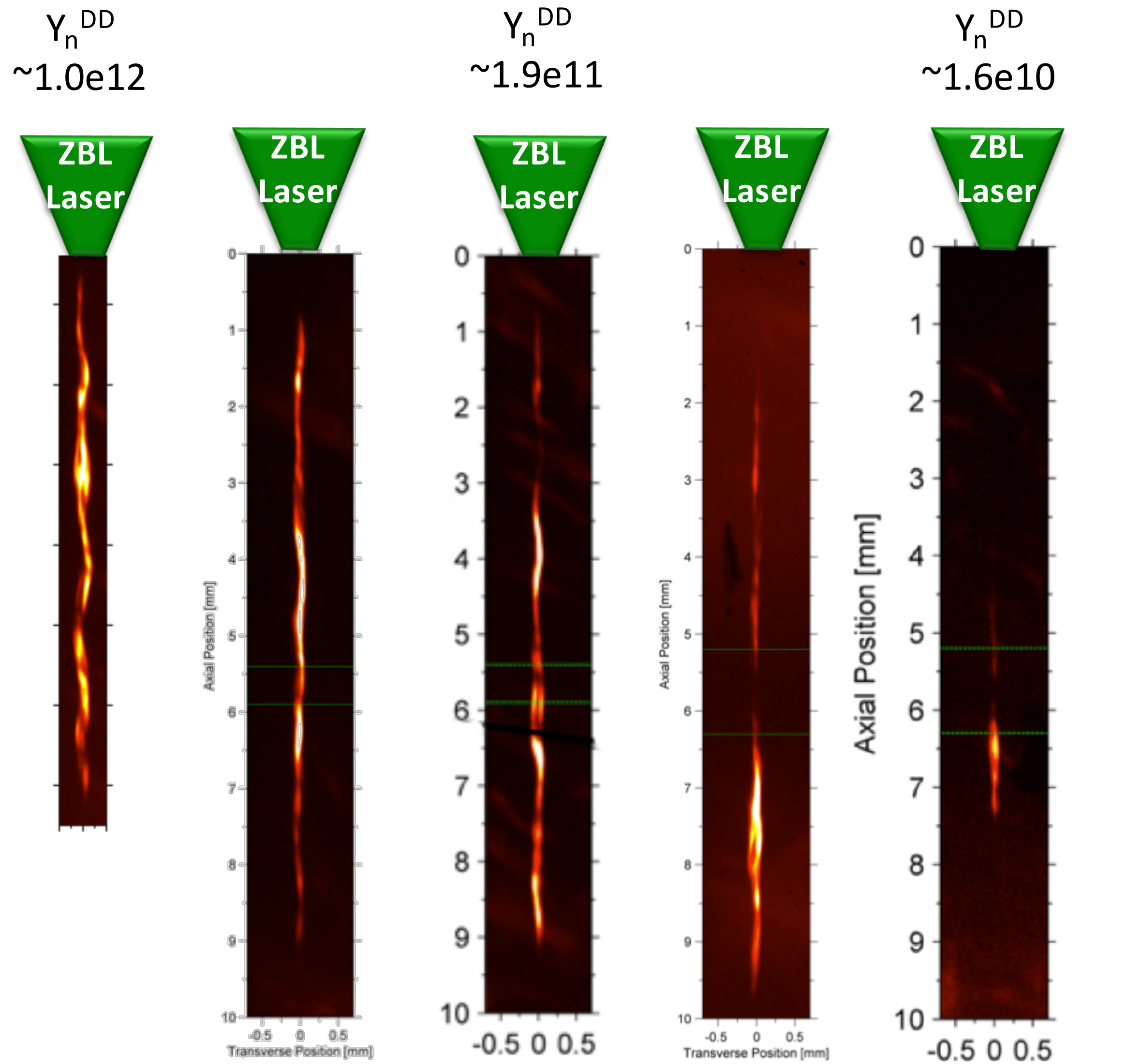
To date, increased laser energy has reduced yield, consistent with *Z*>1 mix from the window and LEH

Simulations:
Increasing laser energy (E_{laser}) from 200 J absorbed to > 1 kJ should *dramatically increase* yield (in absence of mix)

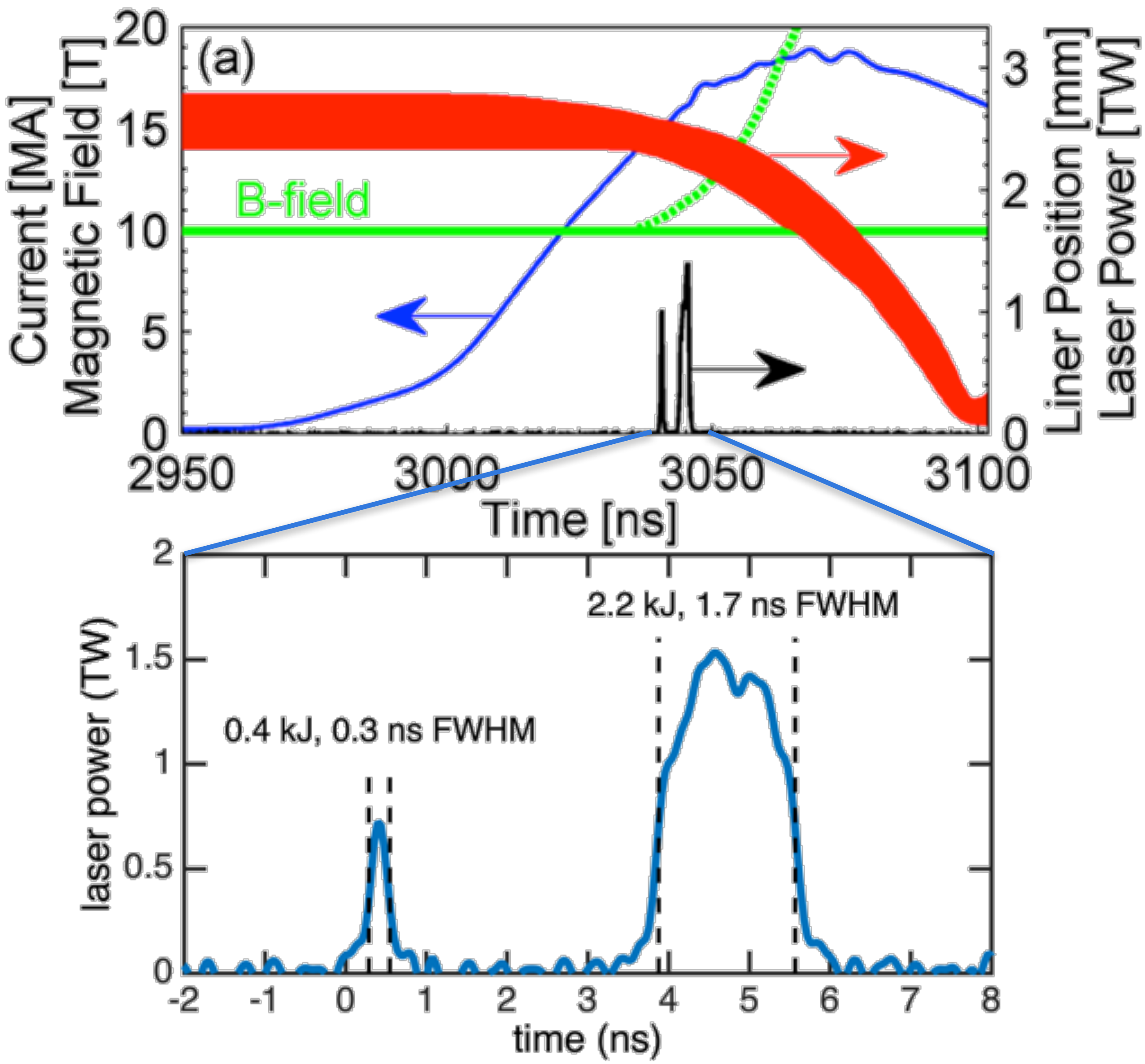
Experiments to-date:
Target changes thought to *increase* laser absorption into gas have all *decreased* the yield.

Laser-produced mix (direct or indirect via blastwave of radiation) appears to be the culprit.

Must stay unmixed for ~50 ns!
We can dud the top of the stagnation plasma!



MagLIF time scales



MagLIF employs a slow implosion (70-100 km/s) so preheat and magnetization are required to achieve thermonuclear conditions

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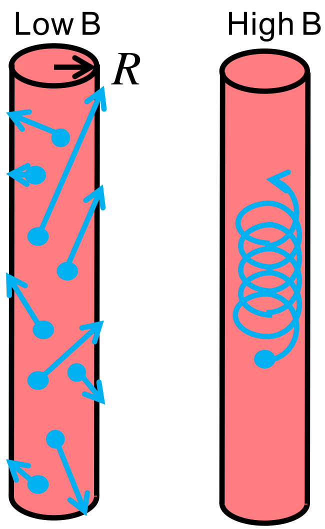
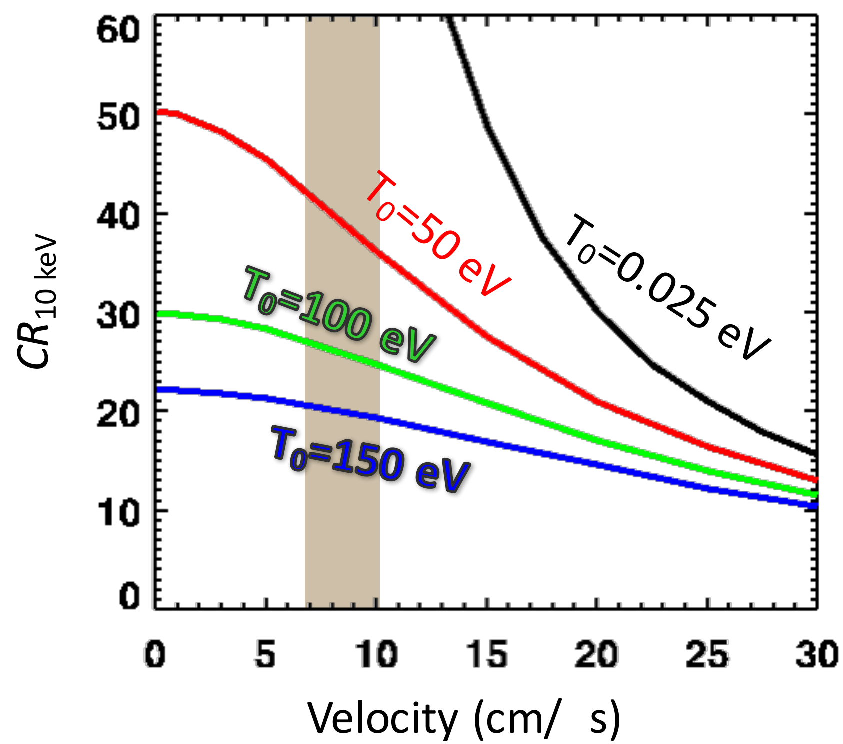


- **Initial 10-30 T field greatly amplified during the implosion through flux compression**
- **Magnetization (“BR”) reduces ρR requirements for α deposition and minimizes electron heat losses***

Simulated CR necessary to achieve T = 10 keV

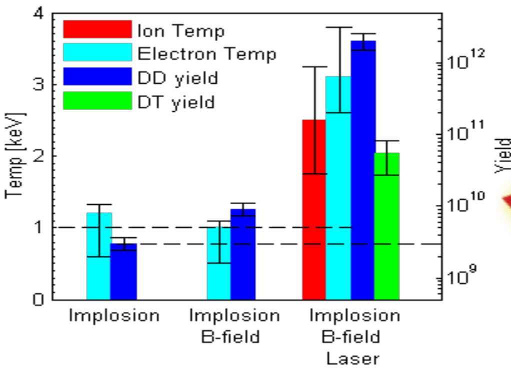


To realize the benefits of preheat, losses must be mitigated during the implosion

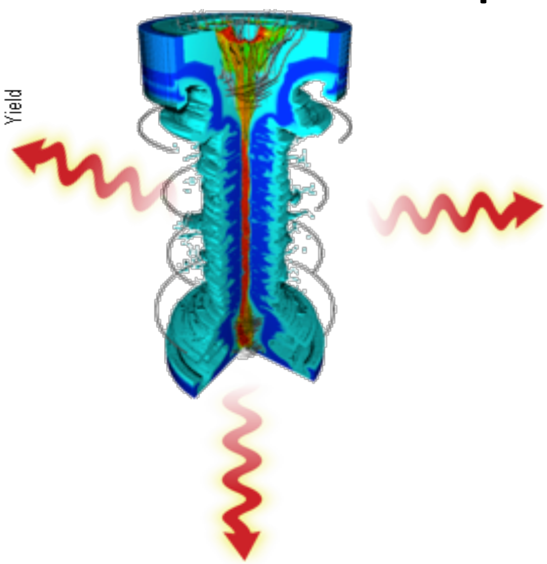
*P.F. Knapp *et al.*, Phys. Plasmas **22**, 056312 (2015)

An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

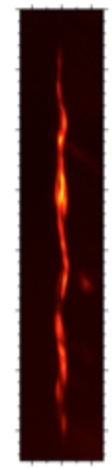
Nuclear Activation (yield)



MagLIF Z pinch

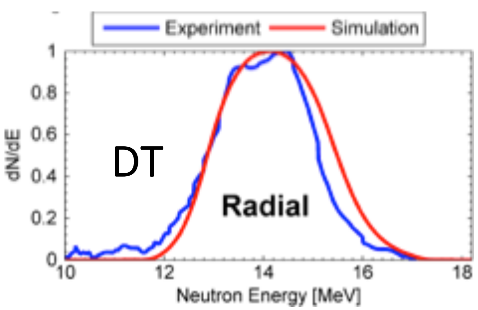


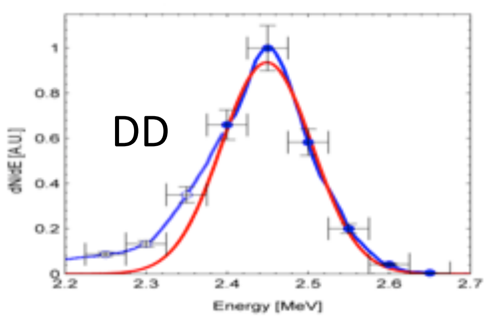
X-ray Imaging (hot plasma shape)



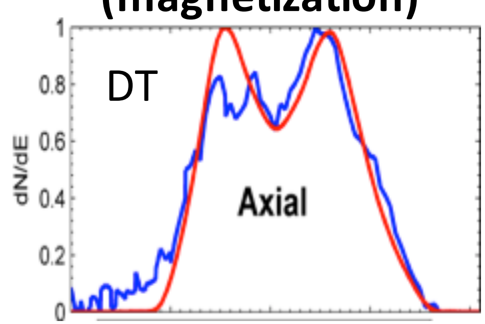
M.R. Gomez *et al.* PRL (2014).
P.F. Schmit *et al.*, PRL (2014).
P.F. Knapp *et al.*, PoP (2015).
M.R. Gomez *et al.*, PoP (2015).
S.B. Hansen *et al.*, PoP (2015).

Neutron spectra (Tion)

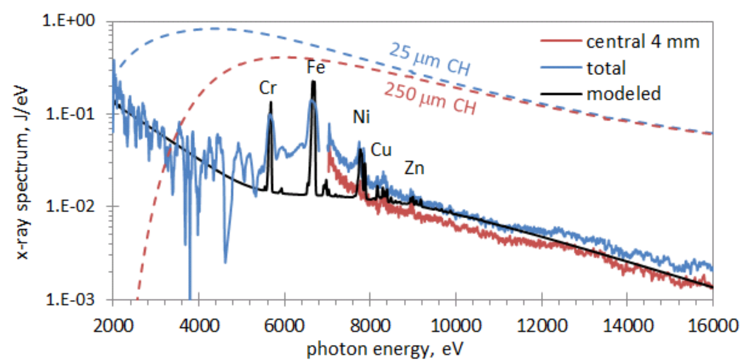




DT Neutron spectra (magnetization)



X-ray Spectra (Te, mix)



Timeline of Proposed Experimental Objectives on NIF

- Year 1
  - Examine efficiency of **coupling** and level of backscatter as function of **laser intensity**
  - Determine laser smoothing effects, level of LPI, on gas heating as well as requirements for predictable behavior with current simulation codes
- Year 2
  - Assess LPI **thresholds**, effect of **gas Ne**, **window thickness** and **pulse shape** on energy coupling
  - Study **impact of magnetic field** on laser propagation (warm)
  - Study **sources of mix** including radiation ablation and blastwave interaction
- Year 3
  - Assess **mix mitigation strategies** for promising scaled designs
  - Study impact of **magnetic field on laser propagation (cryo)**
- Year 4
  - Utilize **Thomson scattering** to quantify fuel conditions
  - Measure **plasma heating lifetimes** with and without magnetic field
  - Demonstrate effective **mix mitigation**
- Year 5
  - Qualify Z300 MagLIF preheating target